

River bank erosion and channel evolution in sand-bed braided reach of River Chenab: role of floods during different flow regimes

Muhammad Ashraf¹ · Muhammad Tousif Bhatti^{2,3} · Abdul Sattar Shakir⁴

Received: 1 May 2014 / Accepted: 18 September 2015 / Published online: 24 February 2016
© Saudi Society for Geosciences 2016

Abstract Braided reaches of large rivers in alluvial plains show major morphological changes, particularly the external bank erosion, due to the flood events. This paper highlights the bank erosion and channel evolution induced by eleven different flood events in a 7-km long reach of the River Chenab, Pakistan. The impact of floods on river bank erosion and channel evolution is analyzed under low and high flow conditions. Flood-induced changes, for river's external banks and channel evolution, were assessed by processing Landsat ETM+ images in ArcGIS tool, and their inter-relationship is evaluated through regression analysis. The results revealed that the major morphological changes were triggered by the flood events occurred during the high flow or *Monsoon* season (July–September), whereas the flood events of similar magnitude occurring during low flow season (October–March) did not induce such changes. Mostly, the erosion remained limited to the middle part of the reach, where the branch channel flows along the bank. The average annual bank erosion rates are much higher as compared with a global scale. Data analysis

showed a strong correlation between the mean high flows and total bank erosion indicating that *Monsoon* seasonal flows and floods are responsible for bank erosion. The present study further identifies the river bank locations highly susceptible to erosion by developing the correlation between bank erosion and branch channel progression. Strong correlation for bank erosion could be established with the shift of branch channels position flowing along the banks in braided reaches of sand bed rivers. However, the presence of sand bars along the river banks resulted in reduced erosion that weakens this relationship. The findings of the present study can help develop better understanding about the bank erosion process and constitute a key element to inform and improve river bank management.

Keywords Morphological changes · Floods · River bank erosion · Landsat images

Introduction

River morphological changes take place in response to variations in different variables which can be grouped into four categories: (i) dynamic flow (rate, discharge, roughness, and shear load), (ii) shape and characteristics of the channel (width, depth, slope, shape, pattern, etc.), (iii) sediment load, and (iv) bed and bank material (shape and characteristics) (Biedenharn et al. 2008). In braided rivers, growing sand bars deflects the main stream toward the outer banks and may cause bank erosion. The consistent aggradation of riverbed induces temporal decrease of stream power resulting into widespread braiding. The river braiding in turn causes substantial yearly land loss (Akhtar et al. 2011; Thorne et al. 1993).

✉ Muhammad Ashraf
ashraf_uaf@hotmail.com

Muhammad Tousif Bhatti
tousif.bhatti@cgiar.org

Abdul Sattar Shakir
shakir@uet.edu.pk

¹ Centre of Excellence in Water Resources Engineering (CEWRE), University of Engineering & Technology, Lahore, Pakistan

² International Water Management Institute (IWMI), Lahore, Pakistan

³ Centre of Excellence in Water Resources Engineering, University of Engineering & Technology, Lahore, Pakistan

⁴ Dean Faculty of Civil Engineering, University of Engineering & Technology, Lahore, Pakistan

Many studies have focused on the river planform evolution with the aim of studying the river bank line migration for sand bed reaches (Khan and Islam 2003; Takagi et al. 2007; Baki and Gan 2012; Mount et al. 2013). Kummur et al. (2008) quantified the bank erosion and accretion rates in the Vientiane-Nong Khai section of the Mekong River using hydrographic Atlas and SPOT 5 satellite images of 2.5-m resolution. More recently, Baki and Gan (2012) developed understanding about the erosion and accretion processes from the perspective of discharge rate, width of channel, and riverbed materials. They have investigated the river bank migration and island dynamics of the braided Jamuna River using Landsat images spanning over 30 years (1973–2003).

River morphological changes have been analyzed over different temporal scales in the previous studies. For example, Baki and Gan (2012) have studied these changes over short to long scale. Whereas, Warburton et al. (1993), Brewer and Levin (1998), Winterbottom (2000) and Hooke (2008) have studied morphological changes over medium to long scales. However, these studies are unable to relate morphological changes with specific flood event due to larger temporal scale. Kiss and Sipos (2007) have attempted to observe riverbed erosion, sediment transportation, and accumulation during the rising and falling stages of floods at a braid-scale; however, flood-induced bank erosion process was not taken into account in the study. Bertoldi et al. (2010) assessed the morphological changes induced by six different floods in a 1-km-long gravel bed braided reach of the Tagliamento River, Italy. Flow pulses induced the morphological changes by eroding the banks at the bend apex, and floods were likely to cause network evolution at reach scale.

The monsoon runoff is known to affect the river bank erosion rates (Darby et al. 2013), but the relationship between high flows and the morphological changes (channel network and bank erosion) has not yet been the focus of significant attention. Few researchers have either attempted to quantify the bank erosion and relate the morphological changes with the peak water level (e.g., Bertoldi et al. 2010), or they have investigated the relationship between discharge and rate of change of river width (Baki and Gan 2012). In this context, the present work takes a step forward and analyzes the flood events affecting the bank erosion and their relationship with the shift of branch channels in sand bed braided river reach.

The present study assess the bank erosion rate induced by the flood events under different flow regimes in the braided section of the Chenab River downstream of Marala barrage. The bank erosion due to the selected flood events has been measured by using satellite images. The study provides the understanding about the river bank erosion due to flood events, lateral shift of branch channel, and sand bars location. The aims of this study are the following: (i) to investigate the hydrological events that cause the major morphological changes, (ii) to study the impact of different magnitude floods on bank erosion, and (iii) to develop relation between lateral

shift of branch channels and bank erosion. For this purpose, remotely sensed data is analyzed to investigate temporal morphological changes in the selected river reach.

Materials and methods

Study area

The River Chenab is one of the major tributaries of the River Indus, fed by the snowmelt and monsoon rainfalls drained by the area of about 32,670 km² above Marala Barrage in Pakistan. The mean water yield of the river is 25.17 km³ year⁻¹ (Tariq and Giesen 2012). Chenab River enters Pakistan just upstream of Marala Barrage after flowing through Kashmir. In Pakistan, the total course length of the river up to its confluence with the River Jhelum is about 292 km (Bhatti and Latif 2011). The mean annual discharge of the River Chenab remained 918 m³ s⁻¹ varying roughly from 126 to 8093 m³ s⁻¹ at upstream of Marala Barrage for the period of 2005–2011, covering a wide range of flows able to induce morphological changes. In this study, the analysis was focused on a river reach starting immediately downstream of the Marala Barrage (Fig. 1b). The selected river reach is about 7 km long with an average width of 3.5 km and lies at elevation of 240 m above mean sea level. The morphology is braided with two branches (i.e., main active branch channel on the right side and secondary branch channel on left side), large semistable islands (locally known as *bela*), and few unstable sand bars (Fig. 3a, b). In most of the occasion, branching of the braided river can be grouped into main and subsidiary channels (Dey 2014). We measured the lateral shift of the branches flowing along the banks and the erosion of external banks. The largest *bela* length is about 4.5 km with an average width of 1.5 km. The bed sediment ranges from fine to medium sand in the main river channels (d_{50} of about 0.32 mm), whereas the small islands range from silt to fine sand. The mean river bed slope is 0.2 %. The external river banks have a double layer formation with fine sand (about 20 %) in the lower part and silt and clay in the upper part (Fig. 1c). Therefore, the banks are highly susceptible to erosion and cause widening of the river sections. The average bank height was measured to be about 5 m. River becomes heavily loaded with the suspended sediments due to erosion from the catchment areas and river banks during high flows (e.g., the river flows at Alexandria bridge, located about 40 km downstream of Marala Barrage, carries about 22.1 million t year⁻¹).

Hydrological data and Landsat images

Eleven flood events were selected for detailed analysis out of which four flood events occurred during the low flow (LF) season (i.e., two individual and two consecutive) and the

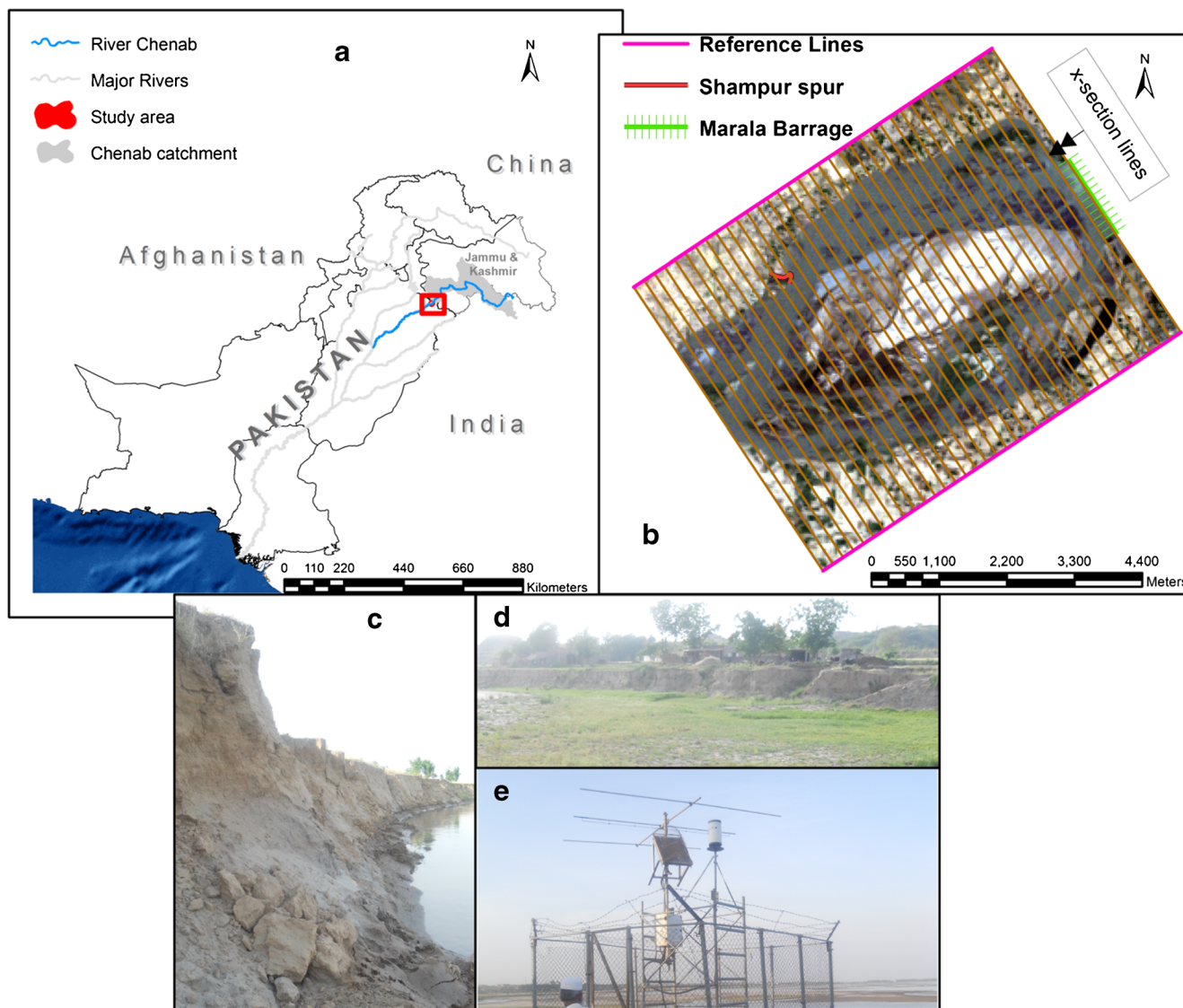


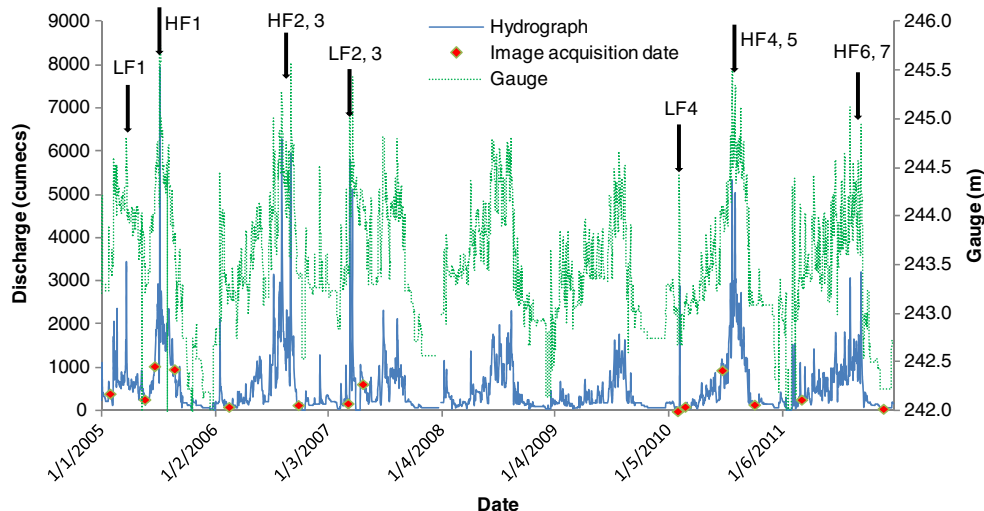
Fig. 1 a Map of Pakistan with some important feature layers including the Chenab River and its catchment area upstream of Marala Barrage. b Landsat image of the study area with the digitized location of Marala Barrage, Shampur spur, reference, and cross-section lines. c Upstream

view of the left bank from Behlolpur about 3 km downstream from Marala Barrage. d Downstream view of right bank from Behlolpur with some settlements near the bank. e Automatic Water level and rain gauge station at Shampur spur

remaining seven flood events occurred during the high flow (HF) or *Monsoon* season (i.e., one individual and six consecutive) (Fig. 2). Table 1 reports the water level and discharge values at the time of occurrence of the selected flood events as well as when the satellite images were acquired. The selection basis for the flood events was a discharge threshold or erosive discharge. Initially, an arbitrary erosive discharge value was set by expert judgment (i.e., only those flood events having magnitude greater than $2835 \text{ m}^3 \text{ s}^{-1}$ were considered for analysis of river bank erosion and channel evolution). Precise values of erosive discharge (under different conditions) are calculated through images and flow analysis. The flood events are termed as HF1 to HF7 for high flow season and LF8 to LF11 for low flow season (Table 1).

A total of 14 Landsat ETM+ images were acquired for this study. For each event (individual or consecutive), the images were acquired in order to ensure that the discharge and water level before and after the event are close to each other to avoid any bias during the comparison of changes in river banks and channels. The available images during the LF and HF seasons of 2005, 2006, 2007, 2010, and 2011 were acquired from the USGS site and processed as explained in the “Analysis of images.” The relationship for average and total annual bank erosion with mean annual and high flows was developed to check the dependency of bank erosion during different flow regimes. Moreover, the relationship between bank erosion and lateral shift of branch channels was developed by using the measurements from the selected images.

Fig. 2 Daily recorded discharge and gauge data downstream from the Marala Barrage during the study period (2005–2011). Vertical arrows are indicating the selected peak discharge/events location on the hydrograph between the acquired images (reported on the plot)



Analysis of images

The images used for the study were Enhanced Thematic Mapper plus (ETM+) with a 30-m resolution downloaded from the US Geological Survey (2012). The selected images were acquired approximately before and after each flood event in order to assess the changes induced by the selected events. The delineation of river channels, external banks lines, sand bars, and the small islands was based on the image bands within the visible range (0.5–0.7, i.e., green and red) and NIR (0.77–0.99) ranges of electromagnetic spectrum. ArcGIS 10.2 software was used to estimate the river bank erosion and movement of channels. All the image bands were firstly combined by using the composite band function. Composite band function combines the different raster bands to form a multi-band image. Various RGB combinations from the bands can be created. For the present study, the bands 2 (green), 3 (red), and 4 (NIR) were used to form a composite image in order to discriminate the different features like channels, sand bars, and islands/vegetation. The composite image was then classified using the Iso Cluster Unsupervised classification (ICUS) within ArcGIS 10.2. ICUS method combines the Iso cluster and maximum likelihood methods to determine the natural groupings in the series of raster images based on the pixel values.

Thirty-four cross sections were selected at 200-m interval along the study reach. The distance from the reference lines to the external banks was calculated by digitizing the lines (as shown in Fig. 1b) to estimate the erosion due to the individual flood events. Barrage axis was employed as reference for the measurements of downstream distances. The identification of the external banks line was difficult at some locations on the images. Therefore, the images were initially classified into five classes and then further merged into three classes: channel, island/*bela*, and sand bar. The composite image also proved helpful to locate the vegetation boundary along the

river. Several studies have used the vegetation boundary along the river flow to successfully indicate the channel boundaries as discussed by Wang et al. (2014). Therefore, the composite images of selected bands together with the classified images by ICUS proved very helpful to identify different spatial features.

Results

Bank erosion due to flood events

Figure 3 shows the braided appearance of the river at low flow stages with branch channels, central semistable islands, and unstable sand bars. The central islands are used as a cultivated land, and the agriculture practices are carried out to grow the crops. The study reach experiences the bank erosion, especially along the right bank, due to the flood events. Average bank erosion rate of the study reach was compared with relationship developed by Van de Wiel (2003) for global bank erosion rate. Van de Wiel (2003) used 221 observations from a wide range of rivers from around the world to estimate the global bank erosion rate (E) in meters per year as a function of drainage area (A) in square kilometers. The equation for the best fit regression line for that data is $E = 0.053A^{0.44}$. Based on this equation, the average erosion rate for the study reach is 5.1 m year^{-1} . However, the estimated average erosion rate for the study period is 34.3 m year^{-1} which is substantially higher because of highly erodible bank material and high and frequent discharges during monsoon. The results show that the study reach of the Chenab River has widened about 6 % during the study period due to erosion, especially of the right bank (Fig. 3d). The volume of eroded sediment along the right bank was calculated about 4.2 million m^3 during the study period.

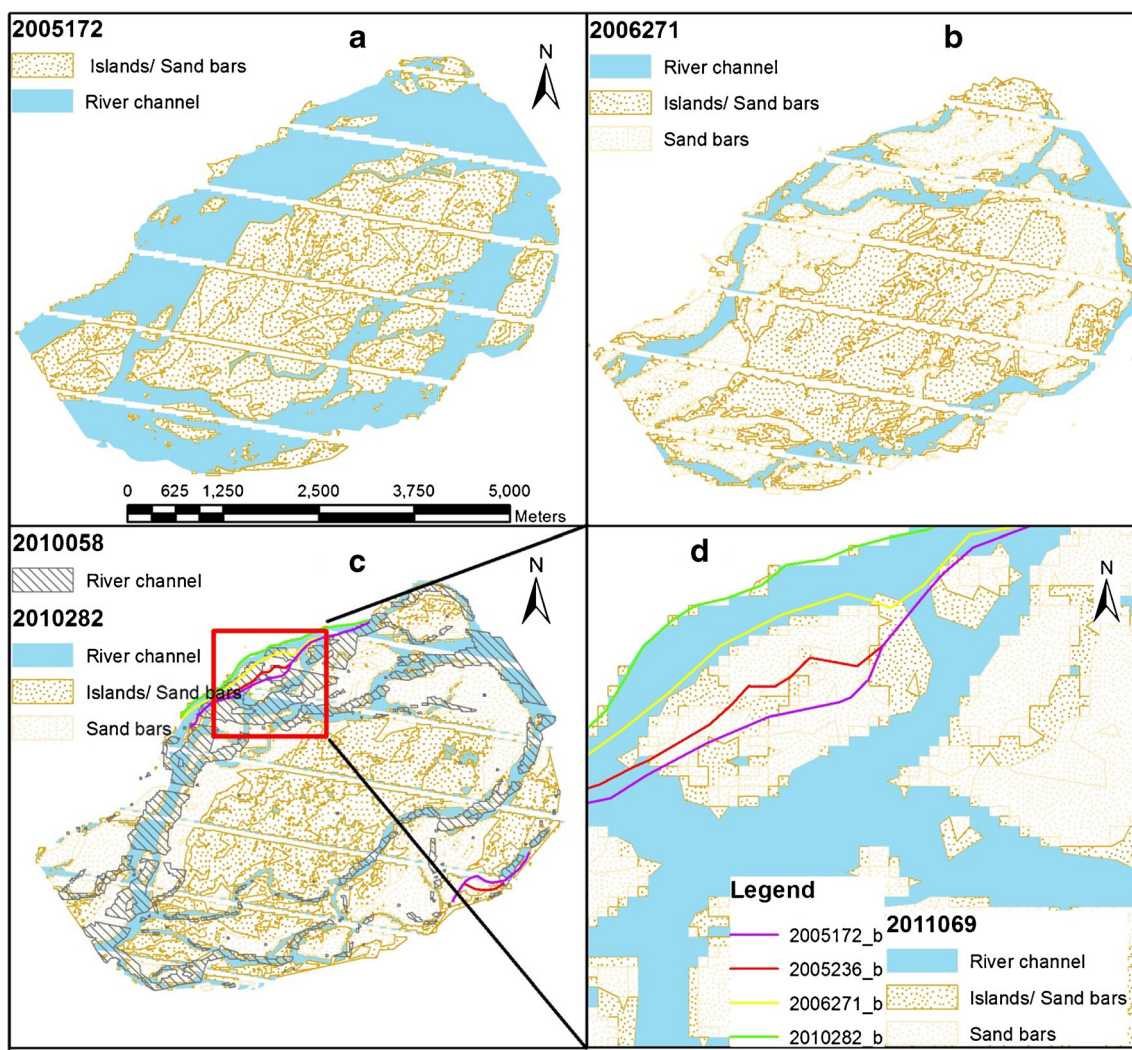


Fig. 3 Classified images (a–d) of major land use classes for different dates with image ID (see Table 1). **d** Shift of bank line after major flood events along right bank of the study reach on classified image of March 10 2011

Bank erosion and channel evolution are simultaneously analyzed through Landsat images. Figure 4 represents the bank erosion due to the major flood events along both banks. The flood event HF1 (during July 2005) eroded the external banks on both sides of the river particularly in the middle span of the braided reach. However, the erosion was observed within a short span of about half a kilometer (ranging from 2 to 2.5 km) along the left bank. The maximum erosion was observed on the left side in the middle span of the selected reach where erosion was about 208 m at 2.2 km downstream of the barrage. At this portion of the reach, external high bank has a concave shape due to which flow followed a curved path. Two consecutive flood events HF2 and HF3, during the year 2006, also eroded the external banks of the river on both sides. Right bank of the river was eroded in the middle of the reach, whereas the left bank was eroded in the upstream portion. The right bank was eroded about 155 m at a distance of 2.8 km downstream of the barrage. The consecutive flood events HF4 and HF5 eroded

the right bank starting from just downstream of the barrage up to the distance of 4.5 km, whereas the erosion for the left bank remained limited to the distance of 6–7 km. However, the flood events during low flow (LF) season did not induce any changes in banks and channels except the consecutive events LF2 and LF3 that caused bank erosion at few locations (Fig. 4). Figure 3 shows that the channel evolution is induced by the flood events HF1, HF2, HF3, HF4, and HF5. These flood events having magnitudes more than $5000 \text{ m}^3 \text{ s}^{-1}$ attained water level more than 245.3 m above sea level during which the braided channel may evolve as a single thread.

River bank erosion versus discharge

To check the dependency of bank erosion with the flood events during two different flow regimes, the relationship for average (Fig. 5) and total annual bank erosion (Fig. 6) with mean annual and high flows were developed. The R^2 between

Table 1 Details of selected flood events and their corresponding Landsat images.

Flood event ID	Raster image ID	Landsat images date	Water level (m)	Discharge during the image acquisition ($m^3 s^{-1}$)	No. of events between the consecutive images	Maximum flood magnitude ($m^3 s^{-1}$)	Peak water level (m)	Flood event date
Flood events during high flow (HF) season								
HF1	2005172	21-Jun-05	244.2	1041	1	7945	246.0	8-Jul-05
	2005236	24-Aug-05	243.8	971				
HF2	2006047	16-Feb-06	243.3	99	2	6256	245.3	5-Aug-06
HF3	2006271	28-Sep-06	243.4	142				
HF4	2010178	27-Jun-10	244.0	949	2	5288	245.5	28-Jul-10
HF5	2010282	9-Oct-10	243.1	153				
HF6	2011069	10-Mar-11	243.4	269	2	3055	245.1	13-Aug-11
HF7	20111129	29-Nov-11	242.2	57				
Flood events during low flow (LF) season								
LF1	2005028	28-Jan-05	243.5	406	1	3437	244.8	22-Mar-05
	2005140	20-May-05	243.5	273				
LF2	2007307	7-Mar-07	243.4	180	2	5758	245.0	13-Mar-07
LF3	2007424	24-Apr-07	244.1	627				
LF4	2010034	3-Feb-10	242.7	0	1	2881	244.4	9-Feb-10
	2010058	27-Feb-10	243.1	104				

bank erosion with mean annual and high flows for right (left) bank was found to be 0.70 (0.21) and 0.74 (0.10) (Fig. 5), respectively. The relatively better R^2 value was found for the right bank indicating the good correlation between bank erosion, and mean and high flows. The reason of weak correlation for left bank is localized erosion as discussed in the first paragraph of “Bank erosion due to flood events.”

The averaging of the bank erosion values weakens its relationship with flows. Therefore, the correlation between mean annual and high flows with total bank erosion was developed. A better correlation was found between the total erosion and mean high flows for right bank than the average bank erosion (Fig. 6). The relationship determined the R^2 values for right bank 0.66 and 0.83 against mean annual and high flows,

respectively. Improved R^2 value indicates that right bank erosion is more dependent on the mean high flows rather than the average annual flows. Therefore, these analyses confirm that the floods and flows during monsoon season are mainly responsible for bank erosion. The analysis of bank erosion shows that the threshold value of discharge to start bank erosion varied under different flow conditions. From the image and flow data analysis, erosive discharge was $5431 m^3 s^{-1}$ during LF season and $3126 m^3 s^{-1}$ during HF season.

River bank erosion versus channel evolution

The previous section (“Bank erosion due to flood events” and “River bank erosion versus discharge”) presented the bank

Fig. 4 Erosion along the right bank (dotted lines) and the left bank (solid lines) due to the selected flood events. Legend represents the flood events ID as given in Table 1

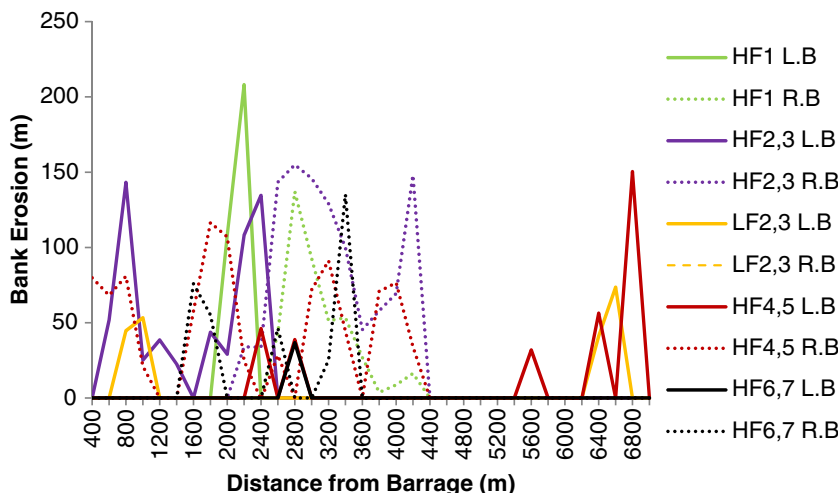
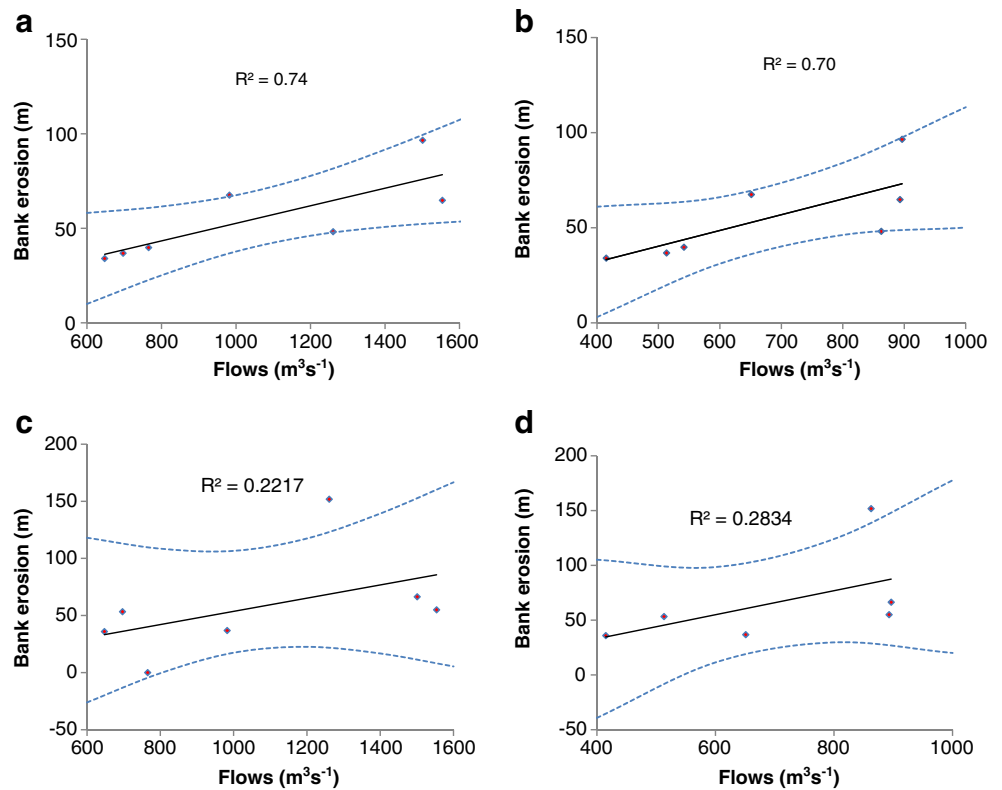


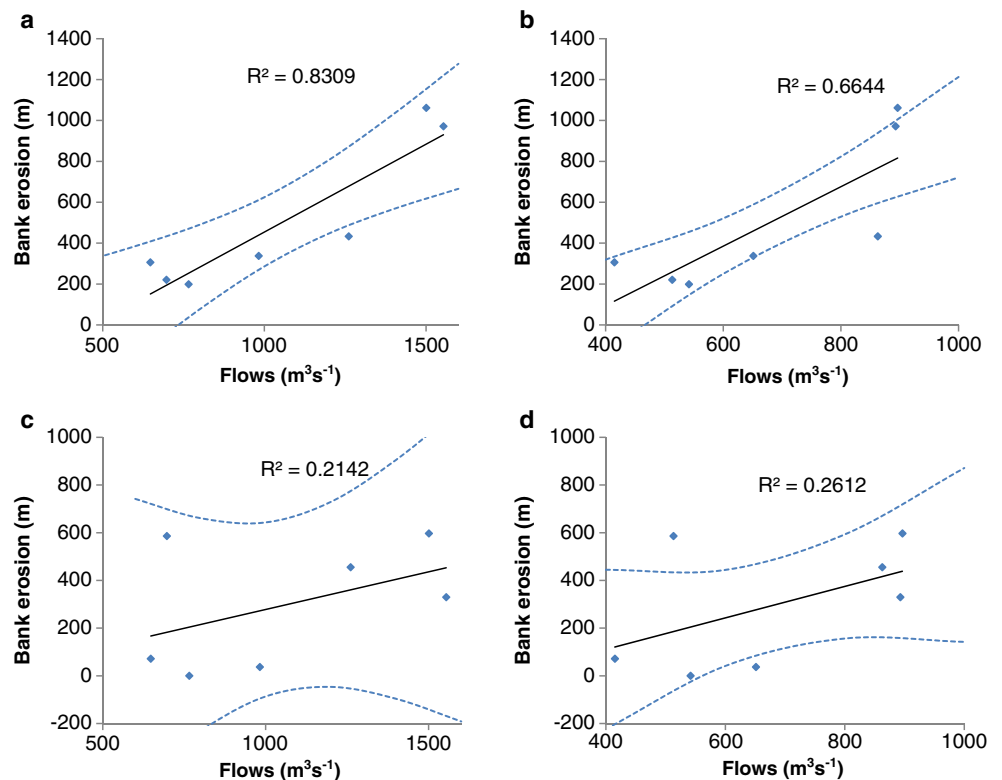
Fig. 5 Regression analysis of average bank erosion with mean high (a) and annual river flows (b) for a 95 % confidence limit: right bank (a, b) and left bank (c, d)



erosion on both sides of the river by analyzing flows and Landsat images. It was observed from the image analysis that the river banks eroded as long as the branch channel flows

along the bank (Fig. 3), whereas the presence of sand bars along the banks keeps the branch channels away from the bank and consequently less erosion along the bank. It can be

Fig. 6 Regression analysis of total bank erosion with mean high (a) and mean annual (b) river flows for a 95 % confidence limit: a, b right bank and c, d left bank



argued from the analysis that presence of sand bars along the right bank appeared as a protection against erosion. To further verify, this argument correlation between the lateral shift of the branch channel along the bank of the river and corresponding bank erosion is developed as shown in Fig. 7. The correlation in Fig. 7a is weak ($R^2=0.31$) because it includes the data points, where branch channel shifts are less due to the presence of sand bars along the bank and the corresponding bank erosion is also very low. In Fig. 7b, the correlation has improved ($R^2=0.79$) by plotting the same data set but ignoring the data points with sandbars. The comparison of Fig. 7a, b suggests that the correlation between bank erosion and lateral shift of branch channel is strong, where the branch channel flows along the bank (or no sand bars are present along the bank) which makes the river bank more susceptible to erosion.

The results of the present study reveal that bank erosion not only depends on the flood events and their magnitudes, but the channel evolution and location of the sand bars are important constituents too. The flood events during the *Monsoon* season are more effective in changing the morphology of the river, especially the erosion of external river banks.

Discussion

Impact of floods

The bank erosion either measured along the digitized lines (Fig. 1b) or perpendicular to the external banks gives close results except for the middle segment of the river reach on the left side. In this segment, the bank erosion was much higher due to the event HF1 (Fig. 4). If the erosion measured perpendicular to the bank, then it results a less value than the measured. The reason of this difference is due to the curved shape of the external bank at this particular section of the reach. All the high flow events induced bank erosion either in the middle and upper parts (along the right bank) or in the lower part (along the left bank) of the braided river reach (Fig. 3). However, the flood events of comparable magnitude did not induce any considerable changes in bank erosion and channel evolution during LF season. The central area of the braided reach remained almost stable due to high bed elevations. During floods, the deposition of sediments occurs on this area and the bed is aggraded accordingly (Coleman 1969). Therefore, the central bars have now become almost stable islands and at a few places crops are grown on these islands. But, these islands of the braided reach are inundated by a certain frequency flood event.

Impact of channel evolution

The right bank erosion during the consecutive flood events HF2 and HF3 was due to the branch channel flowing along the bank. The portion of the reach eroded as long as the branch

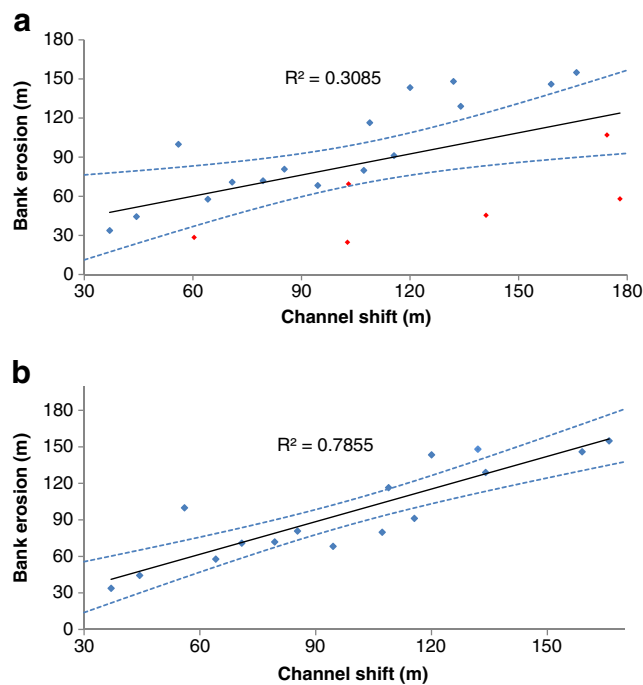


Fig. 7 Regression analysis showing the relationship between bank erosion and shift of river's branch channel from external banks with a 95 % confidence limit: **a** for all the selected locations along the bank and **b** by omitting the points where sand bars are present along the river bank (indicated by red points in Fig. 7a).

channel flows along the right bank (2.6–4 km (Fig. 3b)). The reason of the bank erosion due to HF1 is the same as in the case of HF2 and HF3. The erosion during the consecutive events HF4 and HF5 was due to the removal of sand bar and formation of a new branch channel. The comparison of branch channel network before and after the flood events reveals that the erosion process was initiated with the development of a new branch channel at the upstream location (i.e., 1.4 km downstream of the barrage). This new branch channel was evolved as a result of the removal of a sand bar. Also, the massive erosion occurred at upstream location along the right bank, where the external banks formed a curved shape and the branch channel flows along the bank. Along this curved path, the channel shifted about 70 m toward the external bank due to the erosion. Notably, the external bank erosion took place during the *Monsoon* flood events (HF1 to HF7), particularly during the lateral shifting of branch channel toward the right bank causing erosion up to 155 m. Only these flood events seem to modify the river morphology to a greater extent. These findings corroborate the results of Bertoldi et al. (2010) who observed that the prominent morphological changes are induced by bifurcation evolution that causes a sudden lateral shift of the branch channel position. The discharge distributions in the newly developed channels are controlled by the migration of sand bars.

Abandonment or formation of branch channels and bars dependent on the flood magnitude or water level, as expected,

responds differently in two different seasons. The *Monsoon* flood events caused the abandonment or formation of channels and bars leading to bank erosion, whereas the similar magnitude floods during the LF season did not induce any significant changes in channels network, sand bars, and bank erosion. These results corroborate the previous findings (Darby et al. 2013) that the contribution of monsoon precipitation to runoff is a dominant factor forcing bank erosion. Therefore, the bank erosion and formation and abandonment of branch channels are not only associated with the flood peak but of some other complex conditions. These could be explained by the reduction of shear stresses of flow due to the presence of sand bars along the banks and the moisture conditions of banks. The former condition resists the banks to erode, whereas the later one favors the bank erosion. Hooke (1979) observed that the widespread erosion takes place due to high moisture level in banks. He concluded that the erosion occurs due to high and moderate peaks when bank material is in a moistened condition and removal takes place by collapse and slumping of the material after the peak has passed. Figure 1 shows that the gage data (i.e., the height from mean sea level) remained high even in low peaks during monsoon season. Therefore, the high levels cause the seepage into banks thus causing the bank erosion, because the seepage increases the weight of bank and reduces the shear strength (Pickup and Warner 1976). The result of the present study also corroborates the findings of Bertoldi et al. (2010), who concluded that the flow pulses cause the bank erosion. The analysis of images inferred that the shifting/formation of branch channel eroded the right bank by 155 m which is almost equal to the shifting of channel toward external bank (i.e., 166 m). This suggests that the formation/shifting of new branch channels and abandonment of sand bars along the river bank are primarily responsible for erosion.

Impact of bank protection

Figure 3 shows that the right bank from 4.4 km downstream of the barrage to the end of the study reach remained stable due to the presence of a big spur at Shampur (i.e., about 4.5 km downstream of barrage). A spur of relatively shorter length was also constructed in the middle reach along the right bank, but this spur did not prove helpful for bank protection. The consecutive flood events HF6 and HF7 in 2011 eroded the right bank in the middle reach up to 135 m. After the flood event HF2 and HF3 in 2005, no any major erosion was observed in the central part along the left bank. This might be due to the construction of a big spur at about 2 km downstream of barrage. Therefore, the left bank remained stable due to the protection structure. However, there is no any published reference of such activities along the river banks. These observations about the protection works along the right bank were made during the site visit in April 2012. On the basis of

the available data and images, the present study discussed the major causes and provides the understanding and information about the bank erosion in a sand bed braided river. The results of the study are expected to help managers for the protection works along the river banks.

Conclusions

The rate of bank erosion, channel evolution, and their interrelationship in a braided segment of the River Chenab (Pakistan) was estimated through processing of Landsat images. The results of this study highlighted the effect of seasonal flood events on bank erosion. In particular, the relationship between branch channels shift and bank erosion is investigated. The following points can be stressed from the results obtained after analyzing the hydrologic data and satellite images:

1. The individual or consecutive flood events in the low flow season do not cause the river bank erosion and changes in the channel network of the braided reach, whereas flood events of the similar magnitude during *Monsoon* season cause bank erosion and channel network adjustment. The image analysis also depicts that the formation and abandonment of branch channels are not associated with the floods during the low flow season. The major morphological changes exclusively occurred during the high flow season (*Monsoon* floods). These morphological changes, essentially the lateral shift or formation of branch channels, trigger external bank erosion which in the case of the present study reached 208 m along the left bank at maximum.
2. A strong correlation ($R^2=0.83$) exists between total erosion and mean high flows along the right bank mainly due to diversion of more flows in the right channel of the river. Instead, the same relationship at left bank is weak ($R^2=0.21$) due to the less flow diversion in the left channel of the river. The bank erosion is more dependent on mean high flows than the mean annual flows.
3. The comparison of bank erosion rate of selected river reach with the global bank erosion rate shows that the rate of bank erosion of the Chenab River is much higher and the banks are highly susceptible to erosion.
4. A strong relationship ($R^2=0.79$) between bank erosion and lateral shift of branch channel suggests that within the channel cross section, the rate of bank erosion becomes high where channel flows along the toe. This analysis can be helpful in identifying the bank locations more susceptible to erosion.

The contribution of this paper to the existing literature is threefold. Firstly, it contributes understanding of the channel

evolution and its impact on bank erosion of sand-bed braided river reach in an alluvial plain. Secondly, it provides the insight into the responses of bank erosion to the seasonality of the flood events. Thirdly, it suggests that the bank locations more likely to erode by a specific flood event can be identified by investigating the relationship between bank erosion and lateral shift of branch channels.

Acknowledgments The first author was financially supported by the Higher Education Commission (HEC) of Pakistan within the framework of Indigenous Scholarship Program. This financial support is gratefully acknowledged and appreciated. The authors also acknowledge Dr. Matti Kummu, Assistant Professor at Helsinki University of Technology (TKK), Finland, for sharing valuable information on bank erosion during different flow seasons. The paper greatly benefited from the thorough reviews of anonymous referees.

References

- Akhtar MP, Sharma N, Ojha CSP (2011) Braiding process and bank erosion in the Brahmaputra River. *Int J Sediment Res* 26:431–444
- Baki ABM, Gan TY (2012) Riverbank migration and island dynamics of the braided Jamuna River of the Ganges-Brahmaputra basin using multi-temporal Landsat images. *Quat Int* 263:148–161
- Bertoldi W, Zanoni L, Tubino M (2010) Assessment of morphological changes induced by flow and flood pulses in a gravel bed braided river: the Tagliamento River (Italy). *Geomorphology* 114:348–360
- Bhatti MT, Latif M (2011) Assessment of water quality of a river using an indexing approach during the low-flow season. *Irrig Drain* 60:103–114
- Biedenham DS, Watson CC, Thorne CR (2008) Fundamentals of fluvial geomorphology. In: Garcia MH (ed) *Sediment engineering: processes, measurements. Modelling and Practice*. ASCE, Virginia, USA, pp 355–386
- Brewer PA, Lewin J (1998) Planform cyclicity in an unstable reach: complex fluvial response to environmental change. *Earth Surf Process Landf* 23:989–1008
- Coleman JM (1969) Brahmaputra River: channel processes and sedimentation. *Sediment Geol* 3:129–239
- Darby SE, Leyland J, Kummu M, Räsänen TA, Lauri H (2013) Decoding the drivers of bank erosion on the Mekong river: the roles of the Asian monsoon, tropical storms, and snowmelt. *Water Resour Res* 49(4):2146–2163
- Dey S (2014) *Fluvial hydrodynamics: hydrodynamic and sediment transport phenomena*. Springer, Berlin
- Hooke JM (1979) An analysis of the processes of river bank erosion. *J Hydrol* 42:39–62
- Hooke JM (2008) Temporal variations in fluvial processes on an active meandering river over a 20-year period. *Geomorphology* 100:3–13
- Khan NI, Islam A (2003) Quantification of erosion patterns in the Brahmaputra-Jamuna River using geographical information system and remote sensing techniques. *Hydrol Process* 17:959–966
- Kiss T, Sipos G (2007) Braid-scale channel geometry changes in a sand-bedded river: significance of low stages. *Geomorphology* 84:209–221
- Kummu M, Lu XX, Rasphone A, Sarkkula J, Koponen J (2008) Riverbank changes along the Mekong River: remote sensing detection in the Vientiane–Nong Khai area. *Quat Int* 186:100–112
- Mount NJ, Tate NJ, Sarker MH, Thorne CR (2013) Evolutionary, multi-scale analysis of river bank line retreat using continuous wavelet transforms: Jamuna River, Bangladesh. *Geomorphology* 183:82–92
- Pickup G, Warner RF (1976) Effect of hydrological regime on magnitude and frequency of dominant discharge. *J Hydrol* 29:51–75
- Takagi T, Oguchi T, Matsumoto J, Grossman MJ, Sarker MH, Matin MA (2007) Channel braiding and stability of the Brahmaputra River, Bangladesh, since 1967: GIS and remote sensing analyses. *Geomorphology* 85:294–305
- Tariq MAUR, van de Giesen N (2012) Floods and flood management in Pakistan. *Phys Chem Earth* 47–48:11–20
- Thorne CR, Russell APG, Alam MK (1993) Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. In: Best JL, Bristow, CS (Eds.), *Braided Rivers: Form, Process and Economic Applications*. Special Publication vol. 75. Geological Society, London, UK, pp 257–276.
- US Geological Survey (2012). <http://earthexplorer.usgs.gov/>.
- Van de Wiel MJ (2003) Numerical modelling of channel adjustment in alluvial meandering rivers with riparian vegetation. PhD thesis, Department of Geography, University of Southampton.
- Wang S, Li L, Cheng W (2014) Variations of bank shift rates along the Yinchuan Plain reach of the Yellow River and their influencing factor. *J Geogr Sci* 24(4):703–716
- Warburton J, Davies TRH, Mandl MG (1993) A meso-scale field investigation of channel change and floodplain characteristics in an upland braided gravel-bed river, New Zealand. In: Best JL, Bristow CS (eds) *Braided Rivers: form, process and economic applications*. Special Publication vol. 75. Geological Society, London, UK, pp 241–255
- Winterbottom S (2000) Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology* 34: 195–208