RESEARCH ARTICLE

Assessing the Human Role in Changing Floodplain and Channel Belt of the Yamuna River in National Capital Territory of Delhi, India

Rajesh Kumar[1] · Vijendra Kumar Pandey[1] · Milap Chand Sharma[1]

Abstract

Ongoing demands for irrigation, drinking water supplies and hydropower generation encourage human beings to construct dams and reservoirs on rivers. Such engineering structures together with embankments may protect downstream areas from flooding, can give short-term benefits but may degrade the natural or pristine condition of a river by altering the longitudinal and lateral connectivity of water and sediments. This study analyses the human-induced changes in the channel belt and floodplain morphology of the Yamuna River between Wazirabad and new Okhla barrages using topographic maps and satellite image. In the pre-dam condition (1867–1868), the Yamuna River had a highly braided channel pattern compared to the post-dam situation. After construction of the Tajewala, Hathnikund and Wazirabad barrages, the longitudinal connectivity of sediments and discharge were disturbed so that bar areas were reduced and values of the braided index declined. Dam-induced moderation of peak discharges, rapidly growing population, increasing length of embankments and roads in the floodplain are the major reasons behind the urbanization of Yamuna floodplain in Delhi. This study also shows that the increasing length of engineering structure caused a reduction in channel belt area and its width. Results of the present study are useful for the environmentalists, policy makers and earth scientists working on the restoration and management of floodplain between Wazirabad and new Okhla barrage.

Keywords Channel belt · Braided index · Sinuosity index · Floodplain · GIS

Introduction

Human beings are the active agents to modify the Earth's surface, geomorphic features and natural processes due to advancement in engineering technology over the time (Tarolli 2016; Gregory 2006). Human-induced modifications in natural processes depend on the culture and levels of development of a region (Brown et al. 2017; Kondolf 2018). Human beings have been living in the close vicinity of nature and utilizing its resources for development since the beginning of human civilization. Most of the cities around the globe flourished near the rivers (Yousefi et al.

2017). The flat and fertile alluvium deposition either sides of river attracted more human population therein for agriculture, business and industrial activities with the passage of time (Ward 1978). Due to increasing water demand for drinking, irrigation and electricity generation, human beings started construction of dams and reservoirs across the rivers around the globe. They also constructed embankments and diversion channels to protect cities and agricultural areas from flooding (Ward 1978). The embankments and roads in the floodplain have adverse impacts on channel pattern and morphology (Das et al. 2014). In addition, dams and barrages restrict the longitudinal connectivity of discharge and sediment load from upstream to downstream, while the embankments restrict lateral connectivity of discharge and sediment load from active channel to the floodplain (Wohl 2017).

In recent years, the environmentalists, hydrologists, earth scientists and policy makers realize the adverse impacts of dams in downstream areas of rivers. Dams induce changes in downstream reaches of a river (Williams and Wolman 1984; Graf 2006; Braatne et al. 2008). These

✉ Rajesh Kumar
  rajeshcsrd@gmail.com

[1] Centre for the Study of Regional Development, Jawaharlal Nehru University, New Delhi 110067, India

changes are moderation in discharge and sediment load, modifications in geomorphic features of floodplain and channel planform (Graf 2006; Dai et al. 2014; Smith et al. 2016) and transformation in land use and land cover (Choi et al. 2005; Woldemichael et al. 2012). Sediment deposition in the floodplain and lateral expansion of channel largely depend on a dynamic flow regime. Moderation in discharge and sediment supply by dams disrupts inundation of terraces and floodplain (Shields et al. 2000) and retards sedimentation in the floodplain as a consequence channel incision and changes in channel planform and bar morphology occur (Williams and Wolman 1984; Graf 2006; Schmidt and Wilcock 2008; Gupta et al. 2012; Sanyal 2017; Marcinkowski and Grygoruk 2017). Such moderations also attract high value land use (built-up areas) in the floodplain and changes in natural vegetation. Rapid urbanization along the rivers induces reduction in bar areas and channel width (Yousefi et al. 2017).

Research on the Yamuna River at reach and basin scale has included the land use/land cover change (Chauhan and Gopal 2005; Khan and Bajpai, 2014; Joshi et al. 2011), floods and flood control measures in the Yamuna River floodplain (Vijay et al. 2007; Ahmed et al. 2014; Kumar et al. 2017), stream power-based geomorphic characterization (Bawa et al. 2014), water quality of the Yamuna River (Mandal et al. 2010) and sedimentation in the Yamuna floodplain (Subramanian et al. 1985). Until now, no study has analysed the effects of dams and embankments on the Yamuna channel and floodplain morphology in the NCT of Delhi. Against this research background, the present study aims to analyse the human-induced changes in the channel belt and floodplain morphology of the Yamuna River between Wazirabad and new Okhla barrage. In this context, downstream effects of the Tajewala, Hathnikund and Wazirabad barrages on channel planform changes have been assessed along with the influences of engineering structures (embankment, bridges and spurs) along and across the Yamuna River in the NCT of Delhi.

Study Area

The Yamuna River is one of the major tributaries of the Ganga River in terms of total discharge. It emerges from the Yamunotri glacier that is located near the Banderpoonch peak of the Massourie range of the lower Himalaya and joins the Ganga River at Allahabad (Kumar et al. 2017). The Yamuna has been a lifeline for the north Indian plains since time immemorial as this river was sanctified in the Vedic times, probably realizing its social relevance. There are four barrages, namely Dak Pathar (commissioned in 1965), Hathnikund (constructed between 1996 and 1999), Wazirabad (built in 1959) and new Okhla (built in 1987) for irrigation, drinking water supply to urban areas, flood

control and electricity generation (India-WRIS 2018; Jain et al. 2007). The western Yamuna canal was built in 1355 AD. However, the Britisher built the Tajewala barrage in 1873 and gave a new form to the western and eastern Yamuna canals as irrigation channels during 1870–1882 (Anonymous 2010). After the completion of Hathnikund barrage, the Tajewala barrage was decommissioned. The Agra canal and Okhla weir (located at 2.8 km upstream of the new Okhla barrage) was commissioned in 1874 (India-WRIS 2018). The Yamuna flows across the National Capital Territory (NCT) of Delhi from NNW to SSE direction. The selected study stretch is located between Wazirabad and new Okhla barrage (Fig. 1a–b).

The major geomorphic units of the study area are channel belt, active (Khadar) and older floodplain (Bangar). Channel belt and active floodplain contain newer alluvium, while the older floodplain is occupied by the older alluvium (Kaul and Pandit 2004). Active floodplain is inundated mainly in August and September months during the south-west Monsoons. The highest flood level (207.49 m, a.s.l.) was recorded in September 1978 at Delhi old railway bridge gauge and discharge (G/D) site. The danger level is 204.83 m a.s.l. at this G/D site. The flood depth at this site varies between 0.03 and 2.97 m (Fig. 2). In the NCT of Delhi, the major floods occurred in the year 1924, 1947, 1955, 1956, 1962, 1966, 1967, 1971, 1975, 1976, 1977, 1978, 1983, 1988, 1994, 1995, 1998, 2008, 2010 and 2013 (Fig. 2). The main reason of flooding in the NCT of Delhi is heavy rainfall in upstream areas and release of water from the Hathnikund barrage (Ahmed et al. 2014).

Materials and Methods

The Survey of India (SoI) topographic and antique maps of years 1867–1868, 1910–1911 (53 H/2 and H/6), 1912, 1968–1976 (53 H/2 and H/6) and Sentinel-2 multi-spectral satellite image (dated 21 March, 2017) have been used to map the geomorphic features such as abandoned channel, active floodplain, chute channel, flood deposits, point bar, pond, primary channel, secondary channel, sandy lateral bar, Mid-channel bar (sandy and vegetated) and vegetated alluvial island) and built-up areas with the help of visual interpretation. Engineering structures and built-up areas have also been visually interpreted and mapped using SoI map of 1910–1911 and Sentinel-2 image (Copernicus 2017). The mapping of the Yamuna valley and geomorphic features has been done at 10 m spatial resolution. The co-registration error between Sentinel-2 satellite image, SoI topographic and antique maps remained ± 5 m, only half a pixel.

Flood damage statistics of the NCT of Delhi have been obtained from the Central Water Commission (CWC), New
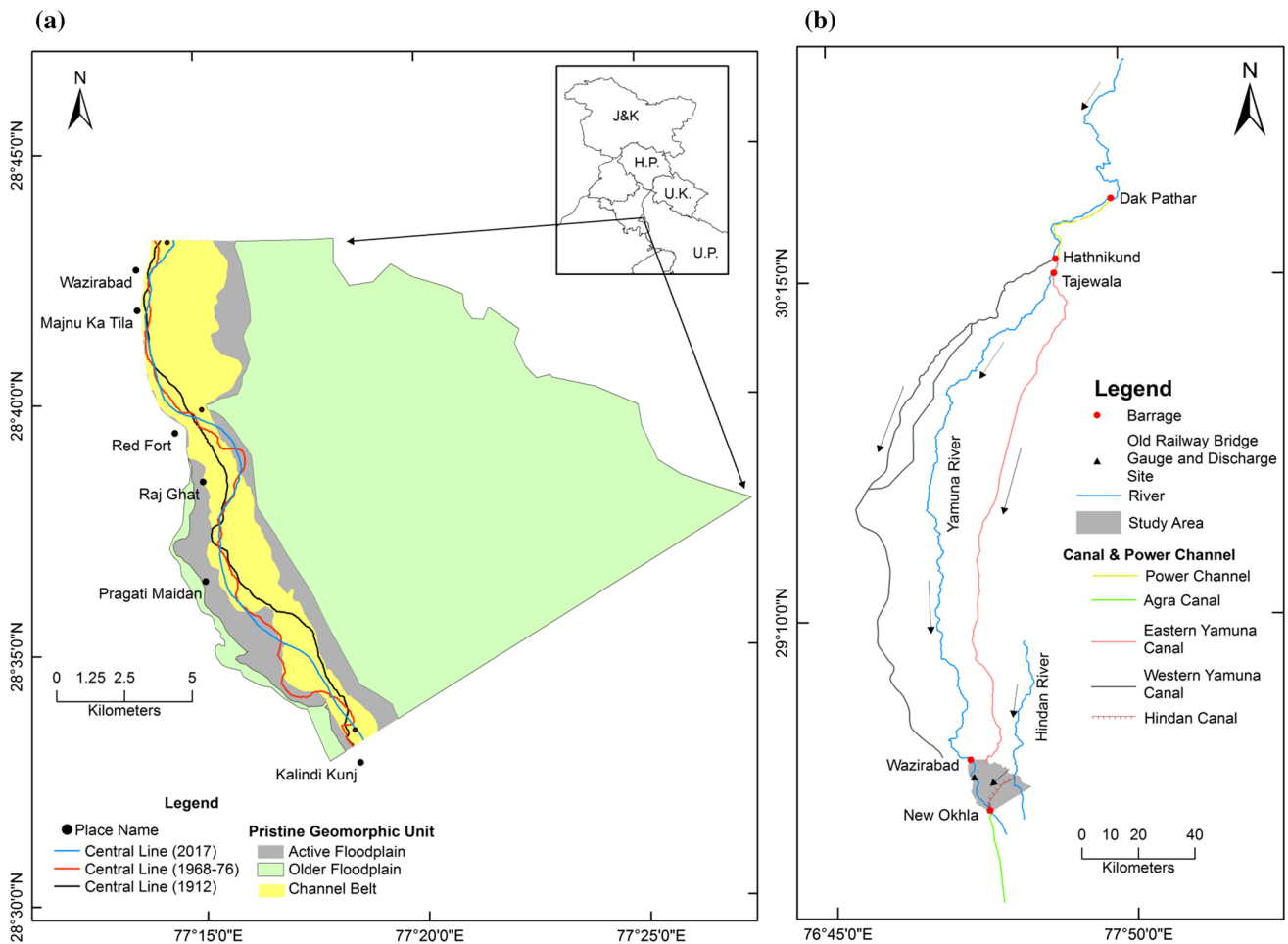
(a)

(b)

Fig. 1 a Location map of the study area. Geomorphic units of the Yamuna River valley between Wazirabad and new Okhla barrage (Kalindi Kunj). The geomorphic features of the year 1912 have been considered as pristine to compare it with the present-day geomorphic units/features and (b) location of barrages and canals in upstream and downstream of the study area

Fig. 2 Deviation of the maximum water level from danger level (1900–2013) at Delhi Railway Bridge G/D Site. Missing data periods are 1901, 1903–191907, 1909–1913, 1915–1923, 1925–1931, 1934–1936, 1938–1941, 1944–1946, 1949–1951, 1953–1954, 1960, 1970, 1979 and 1982
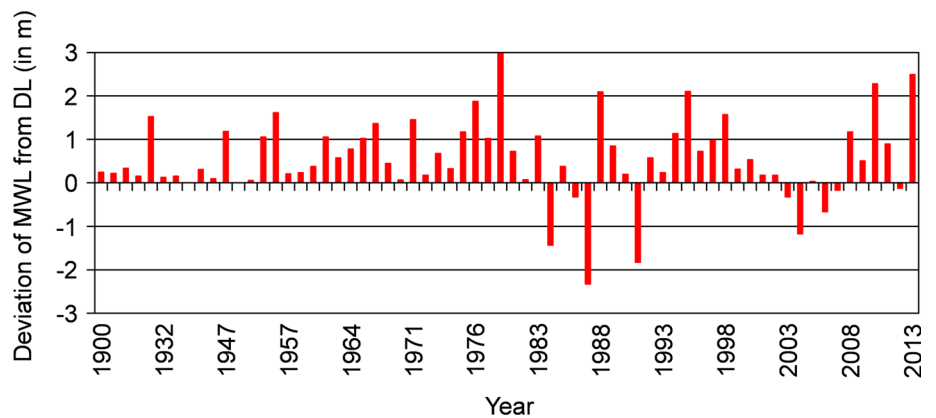
Delhi (CWC 2012). The maximum water level data recorded at Delhi old railway bridge G/D site have been collected from the CWC, New Delhi.

The primary and secondary channel has been differentiated on the basis of flow width. In this study, the channel belt area mainly covers active, chute and secondary channels, point bar, lateral bar, mid-channel bar and alluvial island (Kumar et al. 2013). The width of channel belt has been measured at 500-m interval from upstream to downstream in the GIS environment with the help of transects. In this study, linear and areal properties of geomorphic features and units have been computed using

Table 1 Geomorphic and man-made features and their areal coverage (km^2) (1912–2017)

Geomorphic/man-made features	1912	1968–1976	2017
Abandoned channel	0.3	0.8	0.02
Active floodplain	20.5	34.1	32.4
Chute channel	2.7	0.0	0.0
Flood deposits	0.0	1.0	0.0
Point bar	3.2	1.1	0.6
Pond	0.01	0.1	0.04
Primary channel	5.0	5.5	5.9
Reservoir and Hindon canal	0.0	1.1	1.2
Sandy alluvial island	13.0	0.5	0.0
Sandy lateral bar	0.7	0.7	0.0
Sandy mid-channel bar	1.2	1.6	0.0
Secondary channel	0.6	0.6	0.2
Tributary/drain	0.1	0.3	0.03
Vegetated alluvial island	10.5	0.0	0.5
Vegetated mid-channel bar	1.1	0.0	0.3

Universe Transverse Mercator (UTM) for the zone 43 N along with World Geodetic System (WGS) 1984 datum. Braided (BI) and sinuosity (SI) indices have been
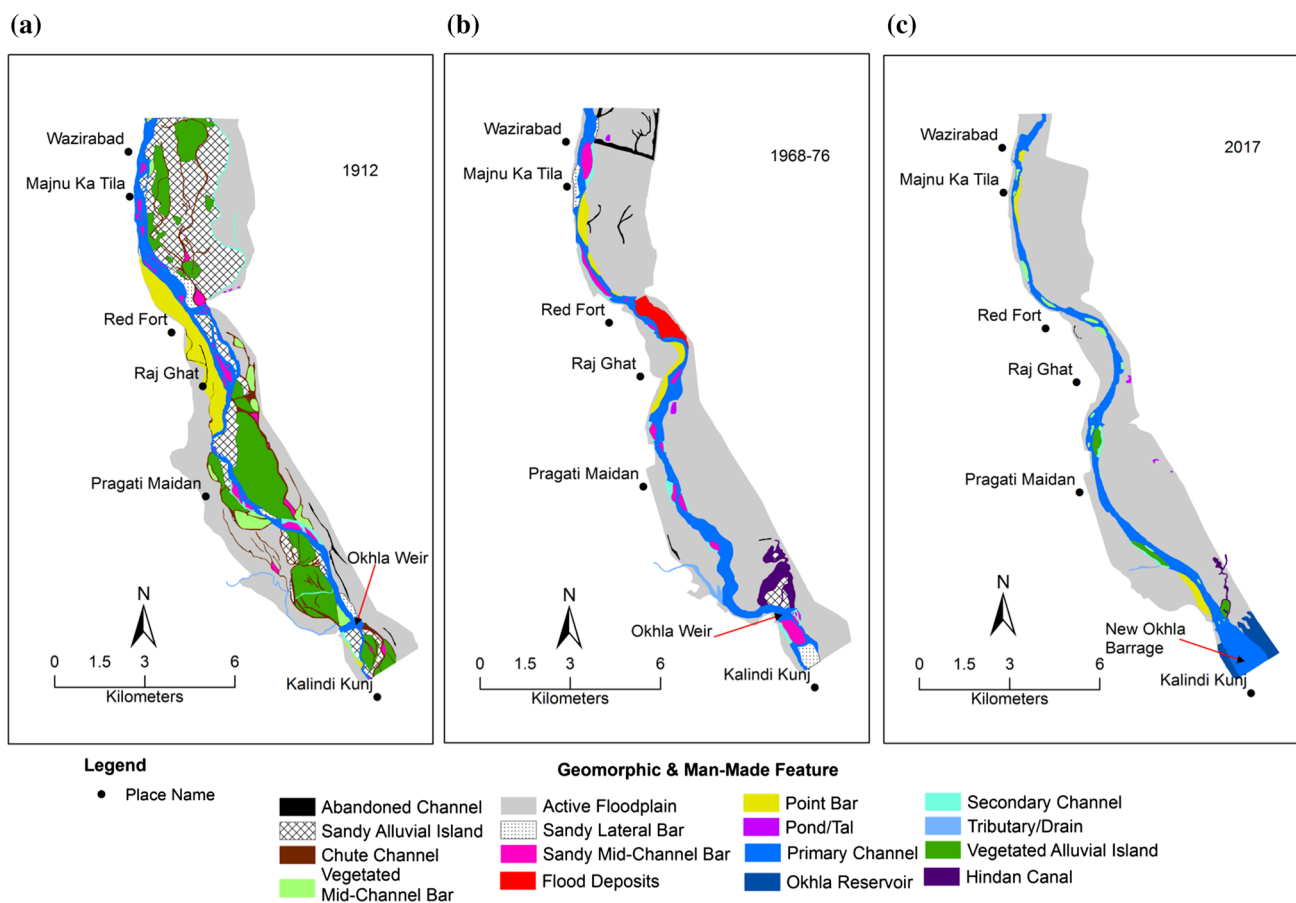
computed to define the channel pattern using Eqs. 1 and 2 (Friend and Sinha 1993).

$$BI = \frac{(\text{Total central line length of secondary \& chute channel})}{(\text{Central line length of primary channel})} \quad (1)$$

$$SI = \frac{(\text{Total central line length of primary channel})}{(\text{Valley length})} \quad (2)$$

Ratio of bar area to channel belt area has been used to define aggradation and degradation in the channel belts of 1912, 1968–1976 and 2017 (e.g., Lahiri and Sinha 2014).

Results and Discussion

Substantial Changes in Geomorphic Features

Significant changes in the Yamuna floodplain have been occurred during 1912–2017. The areal extent of abandoned, secondary and chute channels has been decreasing since 1912. There is a significant reduction in areal extent of point bar, sandy alluvial island, sandy lateral bar and sandy mid-channel bar from 1912 to 2017 (Table 1). The

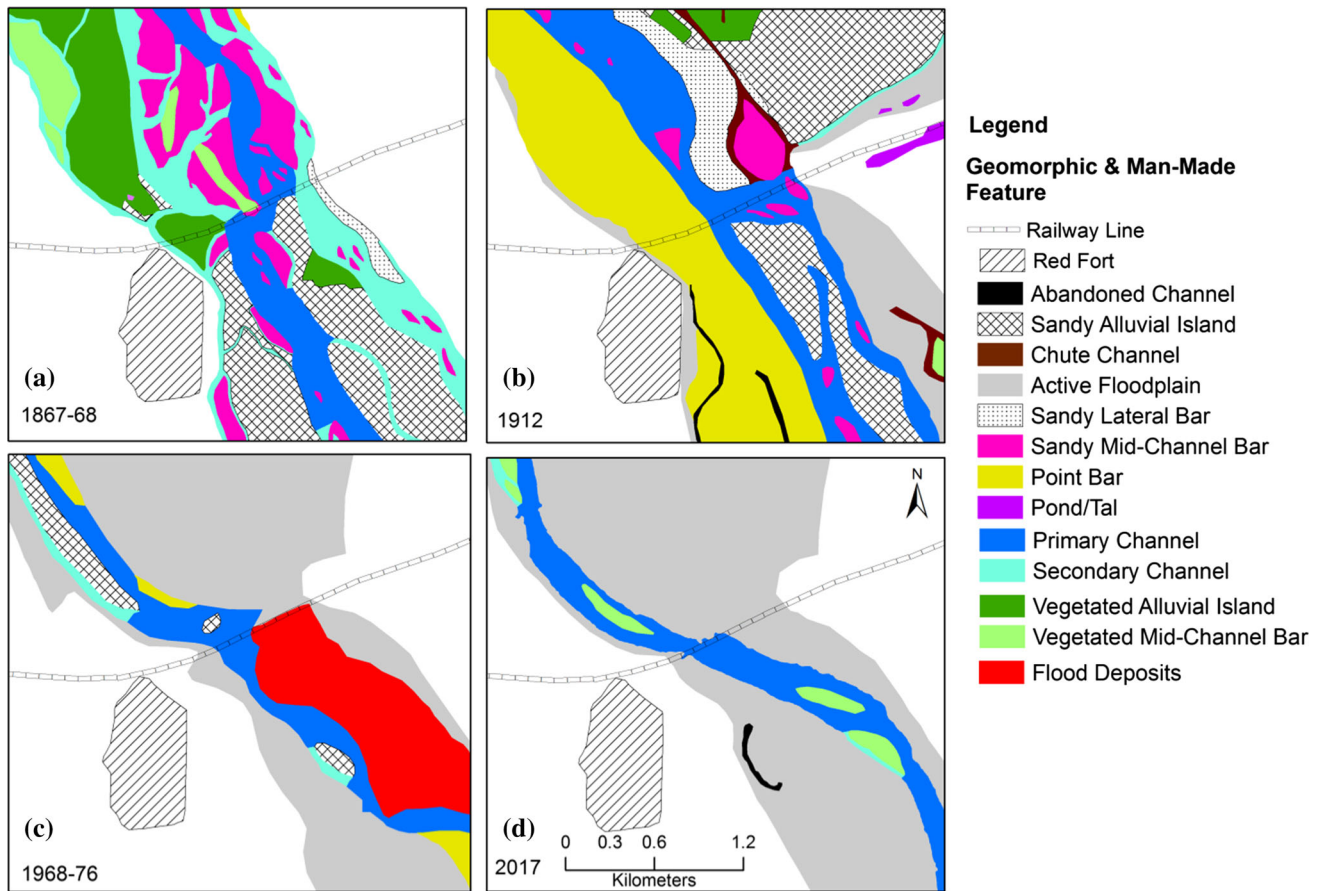**Fig. 3 a–c** Geomorphic/floodplain features in 1912, 1968–1976 and 2017

Fig. 4 **a–d** Changes in floodplain and channel morphology near the Red Fort over the year

Table 2 Change in channel pattern during 1912–2017

Year	Channel length (km)	Valley length (km)	Sinuosity (SI)	Secondary and chute channel length (km)	Braided index (BI)
1912	23.1	20	1.2	51.2	2.2
1968–1976	25.5	20	1.3	9.3	0.37
2017	23.1	20	1.2	3.7	0.16

Table 3 Morphological characteristics of channel belt and active floodplain (1912–2017)

Year	Channel belt width (km)				Channel belt area (km^2)	Bar area (km^2)	Bar/CBA ratio	Active floodplain area (km^2)
	Min	Max	Mean	SD				
1912	0.82	3.39	1.80	0.83	37.5	29.8	0.8	20.5
1968–1976	0.18	0.85	0.49	0.18	10.4	4.9	0.5	34.1
2017	0.10	1.05	0.34	0.19	7.4	1.3	0.2	32.5

area under vegetated alluvial islands and mid-channel bars is also showing an enormous reduction between 1912 and 2017 (Fig. 3a–c). Contrary to such reduction, overall area under primary channel has been increasing since 1912 due to increase in active channel length in 1968–1976 and expansion in the channel just upstream of the new Okhla barrage in 2017. It is also observed that the Hindan canal showed more water expansion in 1968–1976 than that in
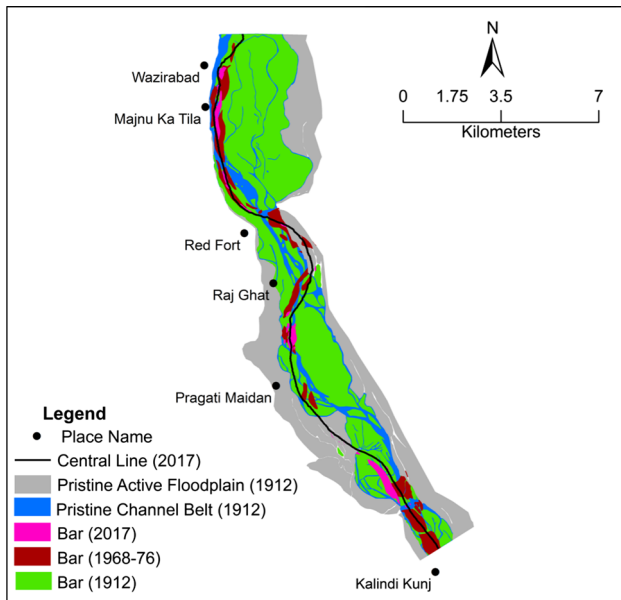
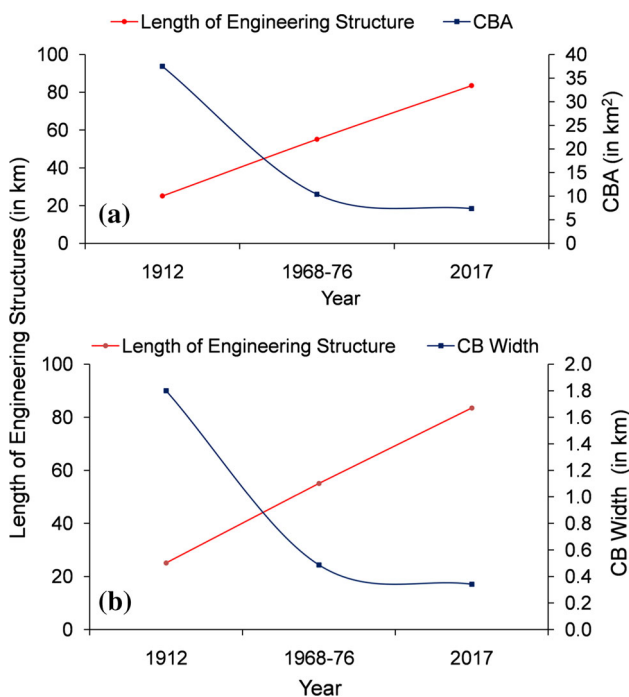**Fig. 5** Floodplain deposits (bars) of different periods

Fig. 6 a–b Association between length of engineering structure, CBA and CB width

2017. Therefore, the geometry of the Hindan canal is mismatching between 1968–1976 and 2017.

Modification in Channel Pattern and Channel Belt

Downstream impact of the Tajewala, Hathnikund and Wazirabad barrages on channel pattern is astonishing. For

this purpose, we selected a stretch near the Red Fort due to unavailability of a map of 1867–1868 for the entire study stretch (Wazirabad to new Okhla barrage). Near the Red Fort, the Yamuna River contained a braided channel pattern during 1867–1868 to 1912 (Fig. 4a–d). The braided index value of the Yamuna River was 4.7 during 1867–1868, while it reduced to 1.9 in 1912 (Supplementary Table 1). Overall, the braided index values are decreasing between 1867–1868 and 2017 near the Red Fort. Thus, in the pre-dam condition (1867–1868), the Yamuna River had a highly braided channel pattern compared to the post-dam situation. The sinuous channel pattern is observed between 1968–1976 and 2017.

Overall channel pattern of the study stretch (Wazirabad to new Okhla barrage) has been changing drastically since 1912. The braided index for this stretch was 2.2 in 1912 and decreased to 0.16 in 2017 due to decrease in bar areas. The Yamuna River shows a sinuous channel pattern as the sinuosity index values vary between 1.2 and 1.3 during 1912–2017 (Table 2). The influence of other two barrages, namely Hathnikund and Wazirabad, which were constructed in the upstream reaches of the study area, is also prominent. Due to natural flow restriction by these barrages, a major component of sedimentation in the Yamuna floodplain of the NCT of Delhi is urban waste rather than natural sediment supply (Subramanian et al. 1985). Approximately 92% of the Yamuna water is used for the irrigation through canals (Central Pollution Control Board 2006). As a consequence, the excess water extraction from the Yamuna caused an imbalance between discharge and sediment load in the river.

An imbalance between discharge and sediment load caused contraction in channel belt (CB). The contraction in channel belt resulted in an increase in active floodplain area in 1968–1976, as compared to 1912. The mean CB width was 1.8 km in 1912 while it is only 0.34 km in 2017 (Table 3). The mean CB width, channel belt area (CBA) and bar area are positively correlated. Bar area directly influences the CB width and CBA (Fig. 5). The ratio of bar area to CBA was 0.8 in 1912, but it is only 0.2 in 2017 (Table 3). In other words, an aggradational process in channel belt was present in 1912 but after 1968–1976, degradational processes are prominent. These morphological statistics indicate alteration in discharge and sediment load. Other factors that caused reduction in CBA, mean CB width and active floodplain area are engineering structures (along and across the flow direction of the Yamuna River) and built-up areas (Supplementary Table 2). After 1968–1976, reduction in CBA, mean CB width and active floodplain has been observed due to increase in the length of engineering structures (Fig. 6a–b).
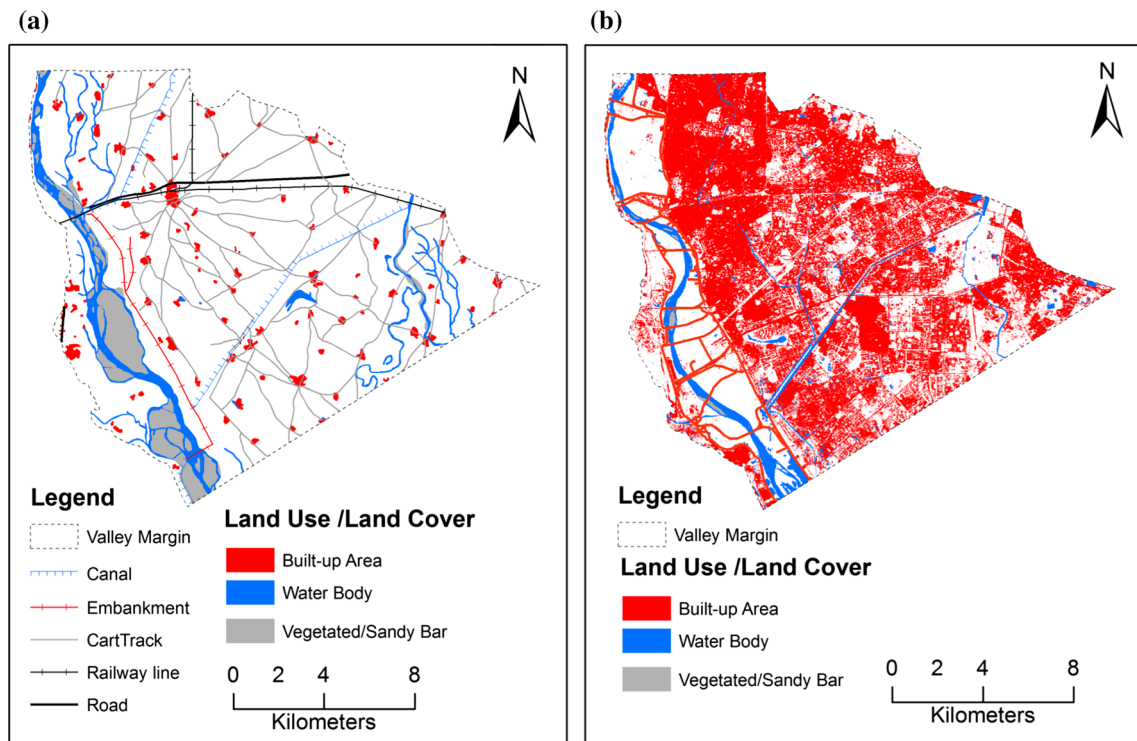
Fig. 7 **a**–**b** Distribution of different land use and land cover in the Yamuna River valley: **a** 1910–1911 and **b** 2017
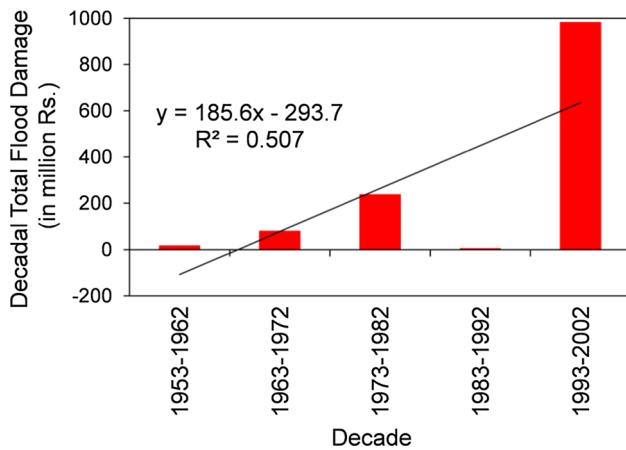

Fig. 8 Increase in decadal total flood damage to crops, houses and public utilities (in million Rs.)

Encroachment of Built-Up Areas on Yamuna Floodplain and Flood Damage

In this study, the encroachment of built-up areas on active and older floodplain has also been analysed. In 1910–1911, the built-up areas occupied 0.9 and 5.3 km^2 area of the active and older floodplain, respectively. However, in 2017, the built-up areas covered 12.3 and 112.5 km^2 area of the active and older floodplain, respectively (Fig. 7a–b). In last 106 years, a substantial increase in built-up areas has been observed in active and older floodplain. One

major reason for the rapid increase in built-up areas is the increasing population. According to Census of India (2011), the total population of NCT Delhi was 0.41 million in 1901 and increased to 16.79 million in 2011.

The Yamuna River floodplain is utilized for metro yards, flyovers, bridges, roads, civic structures and settlements, but the majority of settlements and infrastructures are built in low-lying areas that are vulnerable to floods (Khan and Bajpai 2014; Kumar et al. 2017). Despite controlled flow regime of the Yamuna River by barrages and embankments, the decadal statistics of number of houses damaged due to floods show an increasing trend. During 1953–1962, number of houses damaged due to floods was 7829 but it was increased to 67,043 during 1993–2002 (CWC 2012). This also indicates encroachment of built-up areas on the floodplain of the Yamuna River. Besides this, the decadal statistics of total flood damage to crops, houses and public utilities (in million Indian rupees) also show an increasing trend (Fig. 8).

Conclusions

The altered flow regime due to dams and embankments is the major reason for encroachment of high value land use (built-up areas) on the floodplain as well as for alteration in channel pattern (from braided to sinuous), geomorphic actions (aggradation and degradation) in the CBA and

floodplain. An increasing length of engineering structures along and across the Yamuna floodplain and dams of the upstream reaches are solely responsible for breaking the longitudinal and lateral connectivity of water and sediments that attracted human beings to use the floodplain for various purposes and activities (residential, transport, etc.). During high flow condition, breaches in embankments cause massive damage to houses and infrastructures. Thus, in the NCT of Delhi, human beings modified the natural processes and morphology of the Yamuna River and now the extreme natural process (e.g., floods) is frequently affecting the man-made cultural environment. Hence, the encroachment on floodplain should be restricted by law enforcement in order to reduce the flood-induced damage and to enhance the flood retention capacity of the Yamuna River. The morphological changes in Yamuna floodplain discussed in this study are of enormous importance to environmentalists, policy makers and earth scientists working on the restoration and management of floodplain between Wazirabad and new Okhla barrage.

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