Environmental Management (2014) 53:120–134
DOI 10.1007/s00267-013-0196-4

Channel Characteristics and Planform Dynamics in the Indian *Terai*, Sharda River

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Received: 15 June 2012 / Accepted: 24 October 2013 / Published online: 8 November 2013

Abstract The Sharda River creates and maintains the ecologically diverse remnant patches of rare *Terai* ecosystem in northern India. This study used repeat satellite imagery and geographic information system analysis to assess the planform dynamics along a 60 km length of the Sharda River between 1977 and 2001 to understand the altered dynamics and its plausible causes in this data-poor region. Analyses revealed that the Sharda River has undergone significant change corresponding to enhanced instability in terms of increased number of neck cut-offs and consistent occurrence of avulsions in subsequent shorter assessment periods. An increased channel area (8 %), decreased sinuosity (15 %), increased braiding intensity, and abrupt migrations were also documented. The river has migrated toward the east with its west bankline being more unstable. The maximum shifts were 2.85 km in 13 years (1977–1990), 2.33 km in next 9 years (1990–1999), and a substantial shift of 2.39 km in just 2 years (1999–2001). The altered dynamics is making the future of critical wildlife habitats in Kishanpur Wildlife Sanctuary and North Kheri Forest Division precarious and causing significant economic damage. Extensive deforestation and expansion of agriculture since the 1950s in the catchment area are presumed to have severely impacted the equilibrium of the river, which urgently needs a management plan including wildlife habitat conservation, control, and risk reduction. The present study provides a strong foundation for understanding channel changes in the Sharda River and the finding can serve as a valuable information base for effective management planning and ecological restoration.

Keywords Channel changes · Dudhwa Tiger Reserve · GIS · Kishanpur Wildlife Sanctuary · River dynamics · Flooding

Introduction

Channel migration, annual flooding, and prescribed grassland fires characterize the *Terai* tract in northern India. Channel dynamics represent an integral component in the evolution of vast alluvial floodplain as well as a disturbance regime vital for floodplain patterns and maintenance of a high level of biodiversity. The fluvial action of the Sharda River bordering Kishanpur Wildlife Sanctuary (KWS) and North Kheri Forest Division (NKFD), in the state of Uttar Pradesh, is essential not only for establishing ecologically important remnant patches of the fast-disappearing *Terai* ecosystem but also for maintaining their productivity. The *Terai* tract constitutes a very important habitat for several threatened species found in tall wet grasslands and swamps (Rahmani 1987; Javed 1996) and is of topmost priority for conservation (Rahmani and Islam 2000). Regrettably, in recent decades, recurrent periods of intense flooding in the Sharda River and unpredictable changes in its channel morphology have caused huge losses to the valuable biodiversity of the forest–wetland–grassland complex and to human property.

Alluvial rivers are inherently dynamic in nature, responding to the variation in water and sediment inputs.

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Alterations in inputs either natural or anthropogenic result in changes in the planform/channel pattern, sinuosity, and braiding index (Knighton 1984). Given the constantly changing character, Winterbottom (2000) notes the importance of studying historical channel changes that can prove to be important in understanding the altered river dynamics. Such understanding can assist land and natural resource managers in taking necessary measures to minimize damage (e.g., alterations of aquatic and riparian ecosystems, damage to property) and conserve biodiversity (Gilvear et al. 1999). Thus, Ollero (2010) assessed the channel dynamics and changes in the floodplain in the Middle Ebro River, Spain over the last 80 years and proposed feasible floodplain management solutions. Similarly, Cabezas et al. (2009) studied the hydrologic and landscape changes in this river and proposed a realistic restoration option based on landscape dynamics and the socio-economic context. Tiegs and Pohl (2005) examined the planform channel response of the Colorado River during the period 1976–2000 following alterations to the hydrology to assist resource managers in tailoring a flow regime for proposed rehabilitation of native riparian vegetation.

The Sharda is a mountain-fed river and is part of the larger Gangetic alluvial plains straddling the border between India and Nepal. Flooding during the monsoons is a disastrous natural phenomenon in these alluvial plains of the Gangetic system. The high sediment load and the flatness of the terrain in this region cause the rivers to shift course regularly causing flooding and inundation of forests, agricultural lands, and villages. The human populations in the Nepal *Terai* and in the Indian state of Uttar Pradesh are particularly affected every year by the floods (Moench and Dixit 2004). JBIC (2007) reported that about one fourth of the geographical area of Uttar Pradesh is flood prone. On the basis of 33 years of data (1973–2005), it has been reported that on average 36 districts (out of a total of 70), 14,494 villages, and 2 million ha (m ha) of land (of which 1.16 m ha is agricultural land) are affected by floods every year, and, on that average, 373 human and 1,616 livestock are killed every year with a financial loss of 4,322 million Indian rupees. In the last five decades, the flood management programs on the rivers of the Gangetic plains have largely failed. The available data suggest that during 1954–1990, more than 2,700 billion Indian rupees were spent on flood control measures in India but the annual flood damage increased nearly 40 times and the area affected by floods increased 1.5 times in this period (Agarwal and Narain 1996).

Floods are accompanied by channel movements through avulsion and cut-offs in most rivers in the Gangetic system (Geddes 1960; Chandra 1993; Jain and Sinha 2004; Sinha 2004, 2005; Sinha and Ghosh 2012; Tangri 1992; Jain et al. 2012). While the annual floods are essential for maintaining the productivity of the *Terai* ecosystem, the intensity and frequency of floods and the sediment load seem to have increased since the 1950s (Valdiya 1985; Hamilton 1987; Singh and Dubey 1988; Alexander 1989; Rawat and Rawat 1994; Khalequzzaman 1994; NIOH 1999; Gopal et al. 2002, Jain and Sinha, 2003; Kale 2005; Subrat 2005; Singh 2009; Patnaik and Narayanan 2010; Gupta et al. 2013). Thakkar (2006) reported that the average annual damage in Uttar Pradesh has been increasing over the years. He reported that the average area affected by floods during 1950–1965 was 1.68 m ha, increasing to 2.01 m ha during 1966–1970 and 3.0 m ha during 1971–1978. Notably, in 1978, the Uttar Pradesh witnessed one of the most disastrous floods in 60 years (1953–2010) and the maximum area affected was reported to be 7.3 m ha (GoI 2011). The problem is exacerbated by heavy sediment loads brought down with runoff leading to its deposition on the riverbeds, reduction in the carrying capacity of river channels, and erosion of beds and banks ultimately leading to unpredictable changes in river morphology and course thereof.

Given the dynamic nature of the rivers in the *Terai*, there is a general paucity of hydrological and water-resources studies. The inherent problem with this basin is the dearth of even the most basic data such as river discharge, precipitation within the basin, areas of flooding, and investment in flood control structures (Ramsay 1987; Sinha 2004; Kale 2005). Discharge data in the Himalayan part of the basin are scarce due to lack of measurement stations. Although discharge data from gauging stations have been collected for the downstream part of the plains, these are not available to the public due to the national security laws of India. As a result, most of the hydrology studies carried out in the Ganges (by the government agencies) are classified and are not accessible in the public domain (Bharati et al. 2011). Furthermore, the rivers in this region straddle the international borders between Nepal and India. Both sides of the border have experienced political turmoil at various points of time and the level of cooperation on everything from data collection and sharing, to actual joint management of smaller shared rivers such as the Sharda has been minimal (Everard and Kataria 2010). Under these circumstances, relatively little published information is available on the morphology, hydrology (including flooding history), sediment load, and alternative approaches to flood control (Moench et al. 2009), and what is available is on large scale (Wasson 2003; Jain and Sinha 2003; Sinha 2004; Kale 2005; Sinha et al. 2005; Sinha 2005; Sinha and Ghosh 2012; Jain et al. 2012) and does not capture the local dynamics of smaller but important rivers such as the Sharda.

Notably, the changes in the hydrological regime of the Sharda River have become a matter of growing concern among natural resource managers (Singh 1982; De 2001) and the scientific community (Sale and Singh 1987; Kumar et al. 2002; Islam and Rahmani 2004; Chan et al. 2004; Qureshi et al. 2004; Mitra et al. 2005; Midha and Mathur 2010), as the river borders the ecologically important protected areas and managed forests. The area has witnessed disastrous floods and resultant substantial destruction, four times in the last 50 years: in 1971, 1978, 1989, and 2008. In one of our earlier studies, we recorded a loss of 4.8 km^2 of sal (*Shorea robusta*) forest on the north-eastern boundry of KWS and 1.2 km^2 of grassland from the floodplain area (41.3 km^2) due to shift of the channel toward the sanctuary during the period of 1948–2001 (Midha and Mathur 2010). Further, this proximity is posing threat of inundation to a prime wetland "Jhadi *taal*" in KWS which is one of the major strongholds of the endangered northern swamp deer (*Cervus duvauceli duvauceli*) in India. Along with destruction of forests and tall grasslands, floods also cause significant economic loss. In 2011, flooding of the Sharda River affected 180 villages and over 150,000 people and caused damage to 22,000 ha of agriculture land, damaged rail and road routes, and led to the deaths of 11 people in Lakhimpur-Kheri district of Uttar Pradesh.

Poor baseline data and inadequate scientific information about the changing dynamics of the Sharda River and its causes are serious impediments in designing appropriate strategies and decision making for floodplain management (De 2001; Kumar et al. 2002). Tangri (1992) described the general morphology of the Sharda on a large scale and reported that it is characterized by several westward shifts in different reaches. Mitra et al. (2005) examined the history of channel avulsions in the lower reaches of the Sharda River (where it merges with the Ghaghara River in the Sitapur district of Uttar Pradesh) during the period 1780–2000. Other than that, a few socio-economic studies have evaluated the impact of river management projects on the agriculture sector of the area (Chandra et al. 1979; Chandra and Mohan 1980; Pant 1992; Shah 2001; Sharma 2007, 2010), but the knowledge regarding the altered dynamics in the upper reaches (especially along the protected area); discharge regime, and anthropogenic activities and their hydrological, geomorphological, and ecological consequences remain rather limited (De 2001).

The Government of India proposed to spend 250 million Indian rupees for flood protection works along the left and right banks of the Sharda River in Lakhimpur-Kheri in 2010 (Ganga Flood Control Commission 2012). The protection schemes fail every year, and after each flood dredging and reinforcement of the existing engineering protection work continues and debates continue among river stakeholders, land managers, scientists, and ecologists on floodplain management. The Sharda basin is in dire need of an effective floodplain management plan based on scientific information to conserve areas important for biodiversity and to reduce economic damage.

In view of this, our research primarily aims to assess the planform dynamics on a selected stretch of the Sharda River in India over a period of 24 years using repeated satellite imagery managed in geographic information system (GIS), so as to understand the changes and plausible causes of altered dynamics in this data-poor region. The fundamental geomorphic information would assist managers in the development of a feasible floodplain management plan, which is warranted for the Sharda River floodplain.

Study Area

The Sharda River (known as the Mahakali in Nepal) forms part of the eastern international border between India and Nepal, and originates from the Greater Himalayas at Kalapaani at an altitude of 3,600 m in the Pithoragarh district in the state of Uttarakhand, India. The river borders the Nepalese Mahakali Zone and Uttarakhand and descends to Uttar Pradesh in India (Fig. 1). In its upper reaches, it receives the Gori Ganga River at Jauljibi and the Saryu River at Pancheshwar on the Indian side and the Chameliya River on the Nepalese side (Everard and Kataria 2010). Further down on its course, the Upper Sharda Barrage and Tanakpur Dam in Uttarakand, and Chameliya dam in Nepal are located. Finally, it descends from the Himalaya onto the flat Gangetic Plain of India in the adjacent Pilibhit and Lakhimpur-Kheri districts of Uttar Pradesh. The Sharda Sagar Dam and Lower Sharda Barrage are located in Pilibhit and Lakhimpur-Kheri, respectively. In Lakhimpur-Kheri, the Sharda flows in south-easterly direction and forms part of the boundry of NKFD and KWS. It finally joins the Ghaghra River, which is an important tributary of the Ganga River (De 2001).

The Sharda flows over a distance of 223 km in Nepal and 323.5 km in India up to its confluence with the Ghaghra River. It has a total basin area of 14,871 km^2 up to the Upper Sharda Barrage, about 34 % of which lies in Nepal. The total catchment area is 17,818 km^2 up to the Lower Sharda Barrage (World Bank 1987). The average silt load recorded in the Sharda River in Lakhimpur-Kheri was found to be distinctly high compared to the Ganga (NIOH 1999).

The Upper Sharda was the first barrage commissioned on the Sharda in 1928 to divert water to the Sharda Right Bank Canal, which has a capacity of 396 cumecs, for irrigation in India. India also generates hydropower from it having generation capacity of 41 MW. The Lower Sharda Barrage is located about 163.5 km downstream of the Upper Sharda Barrage, and it was commissioned in 1974.

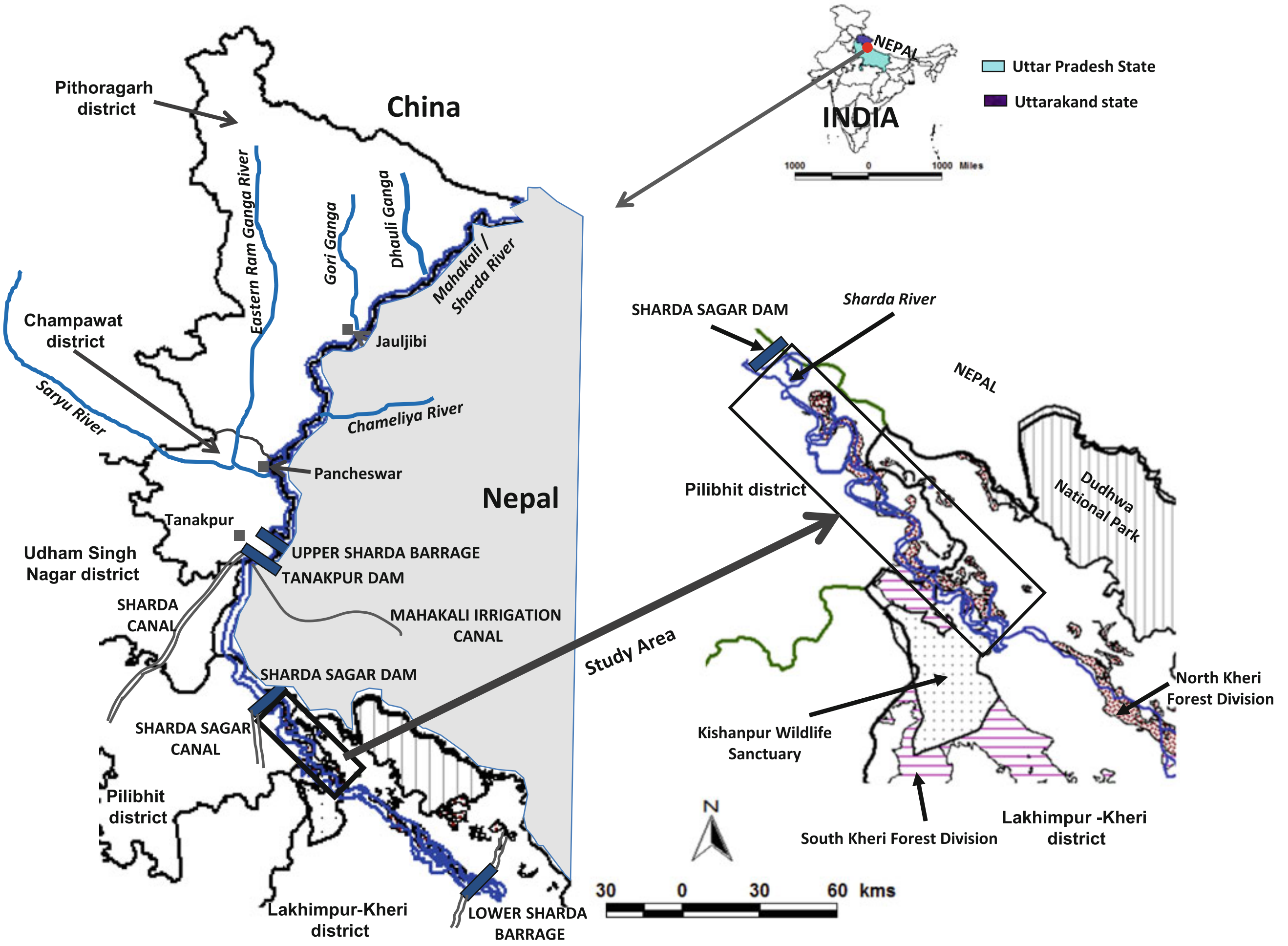

Fig. 1 Location of the study area, a 60-km stretch of the Sharda River bordering KWS and NKFD in the northern Indian *Terai*

A 258.80-km-long feeder channel takes off from the right bank of the Lower Sharda Barrage with discharge of 650 cumecs. The system provides irrigation to an area of 1.674 m ha area in central and eastern Uttar Pradesh (Sharma 2010). Tanakpur Dam, commissioned in 1993 is a gravity type of dam located near the town of Tanakpur in Champawat district, Uttarakand. It comprises a barrage across the Sharda River with a reservoir area of 2,350,000 m^2 and an effective storage capacity of 7,200,000 m^3 (NRLD2009) that diverts river flows into a 6.2-km-long power channel with a generation capacity of 120 MW (Everard and Kataria 2010). Chameliya Dam is located on the Chameliya River in Darchula district, Nepal with generation capacity of 30 MW. In 1957, the Sharda Sagar Dam was commissioned in Pilibhit district for irrigation. It is an earthen-type dam with gross storage capacity of 406,260,000 m^3 and reservoir area of 57,650,000 m^3 (NRLD 2009).

Every year, the silt-laden Sharda River rushes downward disgorging monsoon rainwater from the Himalaya and Shivaliks into the flat Gangetic Plain of Uttar Pradesh, creating and maintaining a heterogeneous landscape of the *Terai* characterized by a mosaic of dense sal forest interspersed with wet tall grasslands, and shallow seasonal swamps (Mathur et al. 2011). The unique complex harbors a variety of floral and faunal life, including several charismatic and obligate species namely the tiger (*Panthera tigris tigris*), Asian elephant (*Elephas maximus*), great one-horned rhinoceros (*Rhinoceros unicornis*), swamp deer (*Cervus duvauceli duvauceli*), hispid hare (*Caprolagus hispidus*), Bengal florican (*Hubraopsis bengalensis*), and pygmy hog (*Sus salvanicus*). Given its conservation significance, two protected areas representing the *Terai*, Shuklaphanta Wildlife Reserve in Nepal and Dudhwa Tiger Reserve (Dudhwa National Park, KWS, and Katerniaghat Wildlife Sanctuary) in India, are located within the Sharda Basin.

The study area comprises 60-km stretch of the Sharda River from the Sharda Sagar Dam to KWS (Fig. 1). The stretch was selected as the Sharda River borders two prominent protected forests, NKFD and KWS here. The study area straddles Lakhimpur-Kheri and Pilibhit districts with the major part in Lakhimpur-Kheri. The river in the study area is described as meandering and is generally wide and shallow with mid-channel bars. The general slope of the area is from northwest to southeast. By and large, the landscape is flat with a narrow range of altitudinal variation, the average being 165 m a.m.s.l. The soil consists of the alluvial formation of the Gangetic plains showing a succession of beds of sand and loam. The average annual rainfall of Lakhimpur-Kheri is 1,090 mm, 90 % of which occurs in the monsoon (July–September) season (Prakash 1979).

Methods

Data and Image Processing

We used the satellite images of 1977 (Landsat MSS—resolution 80 m), 1990 (Landsat TM—resolution 30 m), 1999 (Landsat ETM+—resolution 30 m), and 2001 (IRS 1D, LISS III—resolution 23.5 m) for assessing planform changes in channel over a period of time. All images were from October except the Landsat MSS image which was from March. All datasets were geometrically corrected and resampled to bring to the same scale (Lillesand and Kiefer 2000).

Channel Characteristics

Channel planform changes were studied by assessing channel characteristics which comprises changes in channel morphology, bankline position, length, area, sinuosity, and braiding intensity. For assessing the characteristics, we adopted the methods used by Winterbottom (2000) and Tiegs and Pohl (2005). We digitized the river channel in GIS as one continuous polygon for each year at a scale of 1:50,000. River channel was defined as an elongated area where streamflow occurred with sufficient frequency, force, and duration to preclude the presence of vegetation such that 90 % or greater of the area is bare ground or water (Gurnell 1997; Winterbottom 2000; Tiegs and Pohl 2005). During the year 2005, field surveys were undertaken as part of a project (Mathur and Midha 2008) to understand the present situation and to learn about the perception of the wildlife managers about the changing river dynamics of the area.

Change in Morphology

We divided the digitized river channel of 2001 into six equal segments (A–F) of 10 km each (Fig. 2). The starting point was designated as section 1-1 and the channel reach between section 1-1 and section 2-2 was designated as segment A, and so on. A combined map was prepared by superimposing the digitized river channels of all years to assess changes during different time periods (Fig. 3). Changes in morphology were assessed by visual inspection of digitized channels. A typology mainly based on the methods proposed by Goswami et al. (1999) for planform changes was established. It was used as a base to classify the geomorphological changes observed. The different types of planform changes recognized were: alteration in the direction of flow due to neck cut-off; changes in channel width; development or abandonment of anabranches; and progressive shifting of the meander bends.

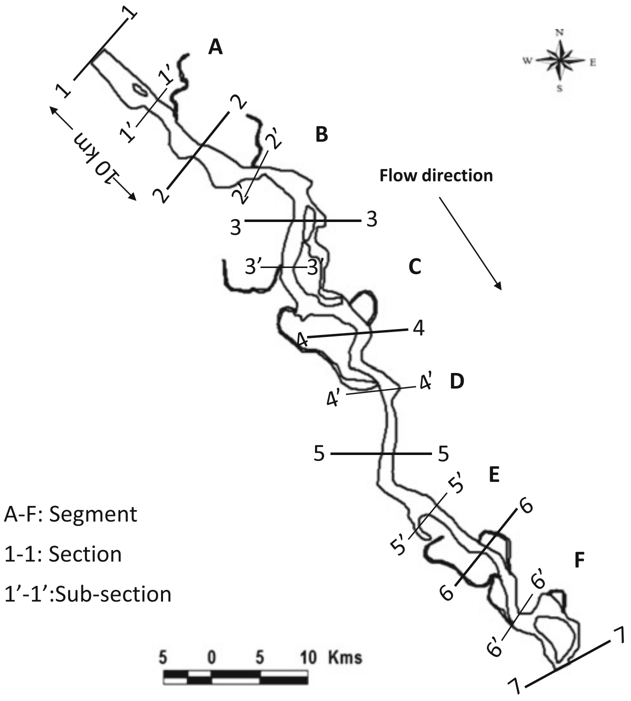

Fig. 2 Channel course of the Sharda River showing the transverse sections, sub-sections, and segments

Amount of Bankline Shift

Each of the six segments were further divided into two equal parts, and the amount of bankline shift was measured at 13 transversed sections (1-1, 1′-1′…..6-6, 6′-6′) as illustrated in Fig. 2.

Changes in Channel Length, Area, Sinuosity, and Braiding Intensity

Channel length was measured along the line equidistant and parallel to the left and right banks of the channel polygon. Active channel area was determined for each polygon in GIS, excluding vegetated mid-channel islands >1.5 km^2 as adopted by Tiegs and Pohl (2005). The line used to determine channel length was also used to measure sinuosity (channel length/straight-line valley length). The braiding intensity was computed as suggested by Brice (1964). The braiding intensity could not be calculated for 1977 due to difference in month of satellite data. The

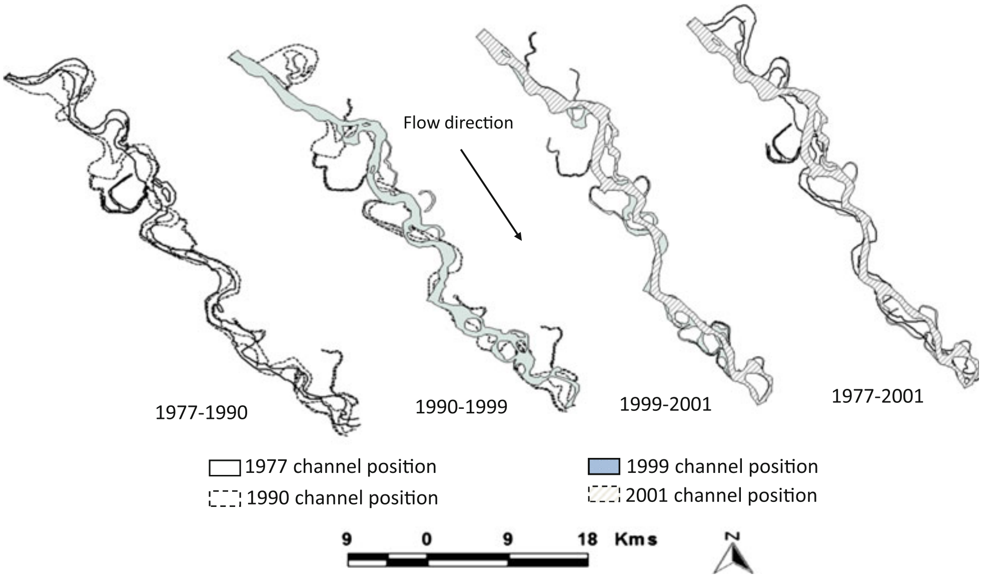

Fig. 3 Channel planform change in the study area, 1977–2001

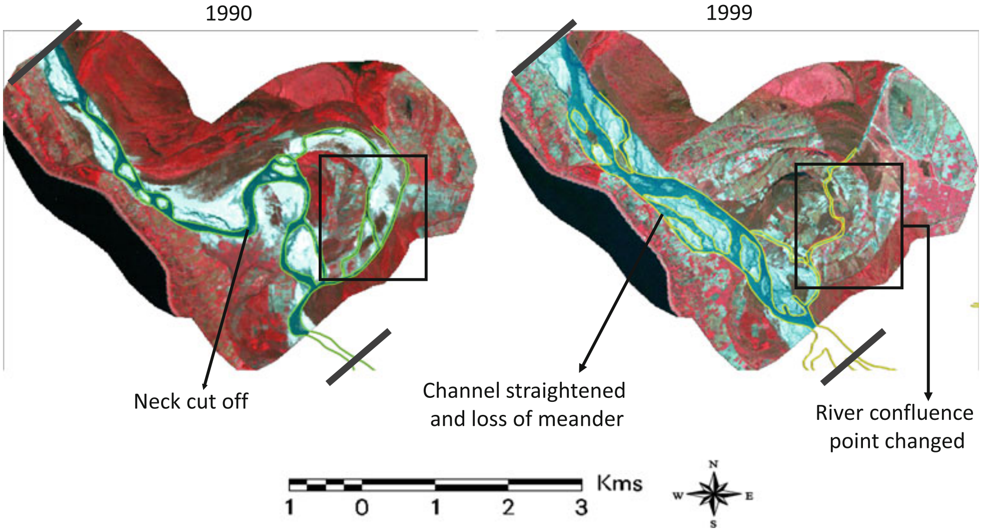

Fig. 4 Satellite imagery of 1990 and 1999 illustrating the episode of channel straightening through neck cut-off in segment A of the Sharda River

channel length, area, sinuosity, and braiding intensity were determined for the entire river channel, for all the assessment periods as well as for each segment.

Results

Planform Changes in the Sharda River

Alteration in the Direction of Flow due to Neck Cut-off

In the beginning of assessment period (i.e., in 1977), there were eight well-defined meander bends within the studied channel of the river. By 1990, one case of neck cut-off was observed in segment B. It led to abandonment of the meander loop and development of another in a new direction of the channel flow. During the subsequent assessment period (1990–1999), three cases of straightening of the river course due to neck cut-off occurred in segments A, B, and E (Fig. 4). The straightening decreased the length of the channel by 3.8, 2.7, and 1.6 km in A, B, and E segments, respectively. Notably, an overall decrease in the total length of the river by 15.3 km from 1990 to 1999 was recorded (Table 1).

One case of straightening of the channel in segment D due to neck cut-off was observed in the period 1999–2001 and the reduction in length was minimal. A significant

Table 1 Channel length at different segments of the Sharda River from 1977 to 2001 (values in parentheses indicate percentage change from previous year)

Segment	Length (km)			
	1977	1990	1999	2001
A	15.5	13.8(−11)	10.0(−27)	10.1(+01)
B	12.4	14.3(+15)	11.5(−20)	10.4(−10)
C	09.7	11.9(+23)	10.8(−09)	10.2(−06)
D	13.5	14.7(+09)	10.2(−31)	09.9(−03)
E	11.8	12.5(+06)	10.9(−13)	10.1(−07)
F	10.9	12.6(+16)	12.7(+01)	11.2(−12)
Total	73.8	79.8(+08)	64.5(−19)	61.9(−04)

event of channel widening due to initiation of neck cut-off and development of new channel was also recorded in 2001 in segment F.

Change in Channel Width

In addition to the reduction in channel length, there were also cases of channel widening and narrowing. The period between 1990 and 1999 registered four instances of channel widening in segments B, D, E, and F which also represent maximum cases of channel widening in the entire time frame of the study. The widening was due to migration of bankline or development of mid-channel islands. During the assessment periods of 1977–1990 and 1999–2001, only one and two cases of widening, respectively, were recorded. During each assessment periods, two cases of channel narrowing were registered. The period between 1977 and 1990 registered channel narrowing in segments B and E while the period 1990-1999 registered channel narrowing in segments A and E. The last assessment period (1999-2001) registered two instances of channel narrowing in segments B and E.

Development or Abandonment of Anabranches

The period between 1977 and 1990 saw the emergence of two new anabranches in segments B and C. Both connected the newly formed meander to the main channel. Segment E was influenced by one case of avulsion wherein the channel abruptly changed its flow direction and shifted to a new position.

By 1999, two new anabranches appeared in segments A and C. In segment A, prior to 1990, a tributary of the Sharda River joined the main channel through a meander. By 1999, the meander was abandoned due to neck cut-off and thus the tributary had to traverse 5.8 km through a newly formed anabranch to join the main channel (Fig. 4). In segment C, avulsion forced the major portion of the flow to the anabranch formed during the period 1977–1990. In 1999, the earlier main channel behaved as an anabranch (Fig. 5).

During 1999–2001, the main channel widened in segment C. This forced the anabranch formed during 1990–1999 to become part of main channel leading to the loss of an anabranch. The process excised two islands from the floodplain. Another considerable change of this period was registered in the lower part of segment E. In the image of 1999, the main channel was found to have widened due to the appearance of three islands. In a span of 2 years (i.e., up to 2001), the flow narrowed in the middle portion and islands became continuous with the adjacent vegetation extracting two anabranches on the east and west banklines.

Progressive Shifting of the Meander Bends

Most of the changes observed in meanders in the different periods conformed to three types of movement: extension, enlargement, and lateral migration.

Amount of Bankline Shift

Assessment Period: 1977–1990

There was a substantial shift of the west bankline during 1977–1990, maximum apparently being 2.85 km at subsection 1′-1′ followed by 1.6 and 1.5 km at sections 3-3 and 6-6, respectively (Table 2). The major shift at subsection 1′-1′ toward the west caused marked increase in channel width between segments A and B. On the other hand, at section 3-3, the shift was toward the east and with less outward movement of the east bankline, this caused channel narrowing. Another narrowing took place at subsection 5′-5′ but here both the banklines contributed equally. Eastward migration of both banklines occurred at section 6-6 and 7-7.

Assessment Period: 1990–1999

During 1990–1999, there were instances of westward shifting of both banklines. At subsection 1′-1′, neck cut-off processes was completed by the year 1999 and both banklines shifted toward the west. At subsection 3′-3′, 4′-4′, and 5′-5′, both banklines showed westward migration. Eastward migration was registered by both banklines at section 1′-1′ and 5-5 (Table 2). At 6-6, the maximum shift of the assessment period took place and the west bankline moved 2.33 km toward the west and the east bankline shifted 0.6 km toward the east.

Assessment Period: 1999–2001

In contrast to the previous assessment period, in this short span of 2 years marked eastward migration of both

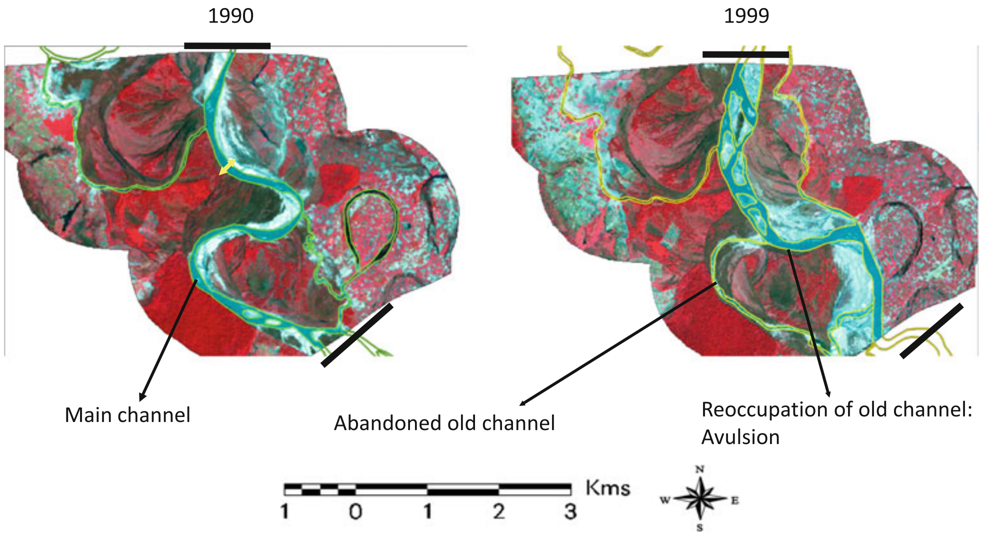

Fig. 5 Satellite imagery of 1990 and 1999 illustrating the episode of avulsion in segment C of the Sharda River

Table 2 Shift in position of banklines (km) of the Sharda River between 1977–1990, 1990–1999, 1999–2001, and 1977–2001

Section/subsection	1977–1990		1990–1999		1999–2001		1977–2001	
	West bank	East bank	West bank	East bank	West bank	East bank	West bank	East bank
1-1	0.17 W	0.00	0.10 E	0.68 E	0.11 W	0.18 E	0.15 W	0.78 E
1′-1′	2.85 W	0.19 E	A	A	0.11 W	0.15 E	A	A
2-2	0.11 W	0.18 W	0.15 W	0.24 E	0.25 W	0.04 W	0.48 W	0.00
2′-2′	–	–	A	A	2.38 E	0.37 E	0.87 E	0.89 E
3-3	1.58 E	0.08 W	A	0.16 E	0.00	0.37 E	1.50 E	1.67 E
3′-3′	–	–	1.45 W	1.29 W	0.10 E	0.00	0.00	0.72 E
4-4	0.40 W	0.52 W	A	A	0.92 E	0.94 E	A	A
4′-4′	0.54 E	0.30 E	0.59 W	0.19 W	0.00	0.00	0.00	0.00
5-5	0.24 E	0.16 W	0.61 E	1.09 E	0.19 E	0.00	0.94 E	1.01 E
5′-5′	0.41 E	0.47 W	0.64 W	0.20 W	0.52 E	0.31 E	0.29 E	0.00
6-6	1.54 E	1.38 E	2.33 W	0.61 E	2.39 E	1.11 W	1.60 E	0.85 E
6′-6′	0.82 W	0.60 W	0.00	0.30 W	0.49 E	0.46 E	0.60 W	0.30 W
7-7	1.40 E	1.46 E	0.16 E	0.21 W	0.26 W	0.00	2.07 E	1.68 E

0.00 no change, *A* abandoned

banklines occurred at section 4-4, subsections 2′-2′, 5′-5′, and 6′-6′ with the maximum being at section 4-4. There were two instances of narrowing at subsection 2′-2′ and section 6-6 and one instance of widening at section 3-3 (Table 2).

Overall Assessment Period: 1977–2001

The overall change indicated an eastward migration of the channel during the entire assessment period. The maximum eastward shift was registered by the west bankline at section 7-7, about 2.0 km. There were only two instances of westward migration of the channel at section 2-2 and subsection 6′-6′. Outward movement of the west bankline toward the west at section 2-2 caused widening of the channel (Table 2).

During all the assessment periods, the maximum shifts were registered by the west bankline. These were 2.85 km in 13 years (1977–1990) and 2.33 km in the next 9 years (1990–1999), with a substantial shift of 2.39 km in just 2 years (1999–2001). In case of the east bankline, the maximum shifts registered were 1.46, 1.29, and 1.11 km during subsequent assessment periods. The minimum shift registered by west bankline was 0.11 km and by east bankline was 0.04 km.

Table 3 Sinuosity values at different segments of the Sharda River from 1977 to 2001 (values in parentheses indicate percentage change from previous year)

Segment	Sinuosity			
	1977	1990	1999	2001
A	1.56	1.39(−11)	1.01(−27)	1.02(+01)
B	1.42	1.64(+15)	1.13(−31)	1.19(+05)
C	1.00	1.32(+32)	1.20(−09)	1.10(−06)
D	1.53	1.67(+09)	1.15(−31)	1.12(−03)
E	1.25	1.32(+06)	1.15(−13)	1.07(−07)
F	1.11	1.28(+15)	1.29(+01)	1.14(−12)

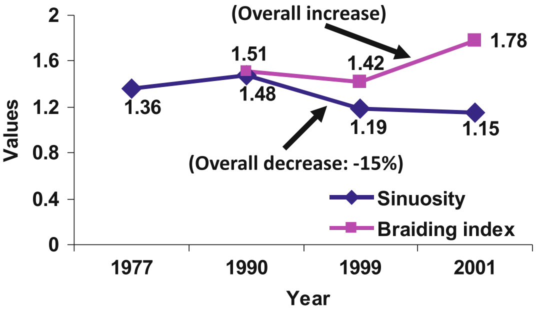

Fig. 6 Variation in sinuosity and braiding index values from 1977 to 2001 in the Sharda River

Changes in Sinuosity, Channel Area, and Braiding Intensity

Values of sinuosity oscillated considerably in six segments during different assessment periods. In 1977, two segments of the channel (A and D) were characterized by sinuosity value of 1.5 indicating a meandering pattern (Table 3). In the subsequent assessment period, the original meandering in segment A lost its sinuosity value by 11 % but there was a gain of 9 % by the other segment D along with gain in all the other segments. The maximum gain, 32 %, was registered in segment C. In the next assessment periods, there was an overall trend of reduced sinuosity. The reason could be the straightening of the river course due to neck cut-off which decreased the length of the channel (Table 1). During the period of 1990–1999, the sinuosity decreased in all the segments except F. The maximum registered loss was 31 % in segments B and D followed by 27 % in segment A. The next assessment period (1999–2001) also experienced downfall with slight gain in segments A and B. While considering the entire stretch of the Sharda River, changes in channel configuration led to an overall decrease in sinuosity by 15 % in 24 years i.e., from 1977 (1.36) to 2001 (1.15) as revealed in Fig. 6. The most significant period responsible for this loss was during 1990–1999 (Table 3).

The river dynamics also influenced the channel area during different periods of assessment (Table 4). The channel area ranged from a minimum of 7.92 km^2 during 1999–2001 (segment D) to 23.87 km^2 in period 1977–1990 (segment A). The maximum gain of 87 % occurred during the period of 1977–1990 in segment A. The gain could be attributed to widening of the channel due to starting of neck cut-off. The next notable gain was recorded in the period 1999–2001 in segment C again due to widening. The other significant gains observed in different segments were: (a) in segment C (42 % during 1999–2001), (b) in segment E (36 % during 1990–1999), and (c) in segment F (27 % during 1990–1999). The significant losses recorded were: Maximum (53 %) in segment A during 1990–1999 due to straightening of the channel due to neck cut-off; followed by 36 % in segment C during the period 1977–1990 due to loss of width (Table 4). The Sharda River registered an overall net gain of 8 % in channel area over 24 years (Fig. 7). The investigated stretch of the Sharda River also showed braiding of varying amount during different assessment periods. The values varied from 1.51 to 1.78. The braiding index value of 1.78 computed for 2001 is relatively high (Fig. 6).

Discussion

This first-time study on the dynamics of the Sharda River generated valuable baseline information on channel characteristics and planform changes over a period of 24 years. The analyses indicated that the Sharda River faced pronounced changes. The 13 years that separated the period of 1977–1990 registered only one neck cut-off and avulsion followed by three neck cut-offs and one avulsion during the subsequent 9 years between 1990 and 1999. However, within the short span of 2 years between 1999 and 2001, one neck cut-off and one avulsion were recorded with another neck cut-off in process. The continuous increasing number of neck cut-offs and consistent occurrence of avulsions in every assessment period indicates incessant increasing instability of the Sharda River. Further, the analysis revealed an overall 8 % net increase in the channel area. Mitra et al. (2005) while documenting the avulsion in lower reaches of the Sharda River from 1780 to 2000 inferred that channel avulsions in the Sharda take place over a time period of 10^1–10^2 years and are triggered by flooding characterized by high discharge and stream velocities. Mount (1995) has also associated neck cut-off and avulsion to heavy flooding. Thus, this increasing instability points toward increase in runoff from upstream. Mount (1995) also elucidated that with the increase in the frequency of the flooding, depositional, rather than erosional, processes act to expand the channel capacity; and

Table 4 Changes in channel area at different segments of the Sharda River from 1977 to 2001 (values in parentheses indicate percentage change from previous year)

Segment	Area (km^2)				
	1977	1990	1999	2001	Overall (% change)
A	12.76	23.87(+87)	11.23(−53)	13.64(+21)	(+07)
B	11.36	11.78(+04)	12.36(+05)	13.84(+12)	(+22)
C	11.44	07.34(−36)	10.42(+42)	16.31(+56)	(+43)
D	11.62	11.88(+02)	11.68(−02)	07.92(−32)	(−32)
E	10.03	10.82(+08)	14.74(+36)	10.66(−28)	(+06)
F	10.99	10.32(−06)	13.14(+27)	11.64(−11)	(+06)

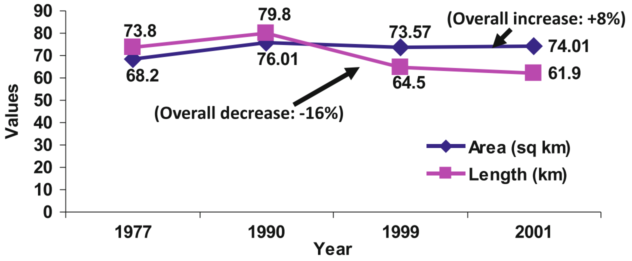

Fig. 7 Variation in values of channel area and length from 1977 to 2001 in the Sharda River

when the discharge exceeds the channel capacity of the river, there is a dramatic increase in the cross-sectional area associated onto the floodplain. Thus, the above argument of increased flooding in the Sharda River was further supported by an overall net increase in the channel area.

Another notable finding of the present study was an overall decrease in sinuosity value coupled with a reduction in the channel length. Additionally, the increased braiding intensity indicates a higher rate of sediment supply from upstream. Goswami et al. (1999) found decrease in overall sinuosity with increase in corresponding braiding intensity in the Subansiri River, Assam, India. They concluded that the river channel seems to make a change from meandering pattern in 1920 toward braiding pattern by 1990 and that the extra amount of sediment that came in must have choked the river gradually and initiated bank erosion and consequently led to channel widening. This observation also seems to be applicable in the context of the Sharda River as overall decrease in sinuosity and increasing braiding intensity have been recorded accompanied by enhanced channel area. The findings of Goswami et al. (1999) and those of our study also support the findings of Burkham (1972), who suggested that over a longer period of time, braiding develops as a result of historic flooding. Friend and Sinha (1993) have also described the negative correlation between sinuosity and braiding in three different types of river (Gandak River: Braided; Burhi Gandak River: Meandering; and Baghmati River: Braided/Meandering) of north Bihar in India.

The analysis distinctly revealed the eastward movement of the entire channel during the entire assessment period. However, the migration was chaotic during the period 1990–1999, where the shift was leveraged toward the west. Tangri (1992) has also mentioned several westward shifts in different reaches of the Sharda River. Mitra et al. (2005) also indicated that there has been a unidirectional lateral migration of Sharda River toward east and related it to the tectonic tilt probably during early Holocene. Similar unidirectional lateral migration has also been observed in the Ganga River (Singh 1996). While the overall trend of movement of the Sharda channel is toward the east, the west bankline has been more unstable compared to the east bankline.

Our confidence in endorsing the statement of incessant increasing instability of the Sharda River is limited by the quality and quantity of historical data available for the Sharda Basin. In data-limited environments common across the Indo-Gangetic plain, it is often impossible to establish an argument regarding such altered dynamics. The daily precipitation data over a sufficiently long period for the basin, the flooding history, and discharge from the dams could not be assessed for the present study. Another limitation was inability to acquire recent satellite data and data related to the same calendar month. Purchasing digital images was beyond the scope of the budget allocated for this project. Due to the difference in the month of satellite data, braiding intensity could not be calculated for 1977. This presented a severe limitation in comparing the increased braiding intensity from the base year and might have underestimated the change in channel area. Nonetheless, the present study attempted to provide insight into channel changes in the Sharda River which could be useful in development of floodplain management plan combining wildlife habitat conservation and risk reduction especially for KWS. KWS and Jhadi *taal* have been recognized as important bird areas and placed under A1 category, i.e., holding species classified as globally threatened with extinction (Islam and Rahmani 2004). In addition, KWS and Jhadi *taal* support a large population of tigers due to abundant prey that includes swamp deer, *Cervus porcinus*, and *Sus scrofa*. Midha and Mathur (2010) raised the concern that the distance between *taal* and the Sharda channel has reduced to less than 10 m as observed in 2008 and the west bankline shifted by 3.1 km southwest toward Jhadi *taal* during the assessment period (1948–2001). Such instability of the Sharda River can prove to be fatal for an endangered species like the swamp deer. Ultimately, swamp deer population will be forced to migrate in search of a new suitable habitat. If it moves outside the protected area, it will become vulnerable to poaching.

Given the lack of sufficient data, in order to comprehend the plausible causes of such altered dynamics, we attempted to understand the history of the Sharda Basin since the time the constantly changing character elicited concerns among natural resource managers and the scientific community. An endeavor has been made to compare the results of the present study with other similar studies around the world to find an empirical means to disentangle the cause–effect relations.

Human History of the Sharda Basin

The probable driving factors for the altered dynamics of the Sharda River could be multiple. The history of the Sharda River is relatively recent as compared to other large rivers. The *Terai* region was inhospitable for a considerable time due to the extensive wilderness, flooding, and the fact that it was a disease (e.g., malaria and influenza) prone area (De 2001; Kumar et al. 2002). The area remained thinly populated for a long time, being occupied by the local tribes (*Tharus*). After the arrival of the Britishers, reserved forests were carved out in the 1880s and forests were heavily worked for production forestry and extraction of timber. Heavy demands for wood during World War I and II put an extra pressure on the forests of the *Terai*. The Upper Sharda was the first dam in the series to be commissioned on the Sharda River in the 1920s. In the following decades, both the Indian and Nepal *Terai* witnessed major change especially after the 1950s with the virtual eradication of malaria. The favorable conditions in terms of flat terrain, fertility, and high water table fostered massive influx of people from the less productive hills. Till 1951, the percentage decadal variation in the human population was less than 10 % for Lakhimpur-Kheri. It increased to 18.9 % in 1961 and till the last census in 2001; it had reached 32.3 % which is even higher than the entire state of Uttar Pradesh (25.80 %) (Prakash 1979; GoI 2001). Analogously, on the Nepal side, the average net gain in the human population in the *Terai* due to immigration was 94.3 % in eight out of 14 districts between 1981 and 1991 (HMGN/MFSC 2002). The migration in both Nepal and India has been followed by uncontrolled intensification of agriculture and the associated large-scale clearing of forest, and reclamation/conversion of grassland and swamp habitats into cultivable land especially on Nepal side. A study by DFRS (2002) revealed that Kanchanpur district, which is one of the districts of Nepal's *Terai* through which the Sharda River flows, lost 17,614 ha of forests between 1978 and 1996. In addition, large-scale land-use changes were also accompanied by various hydroelectric and irrigation projects. Four dams viz. the Sharda Sagar, Lower Sharda, Tanakpur, and Chameliya were commissioned in the subsequent years. Today, the Sharda Basin harbors several small scattered forest fragments amidst vast human- and agriculture-dominated matrix where once extensive contiguous forests of *Terai* existed.

Approach to Comprehend Channel Changes

Wallick et al. (2007) proposed a general framework to link channel changes with their causes. The predictions constitute hypotheses linking geomorphic and anthropogenic drivers with plausible responses, and provide a reasonable means of interpreting historical patterns of channel change. To construct a reasonable narrative of linkage of channel changes in the Sharda River and human activities, we summarized the anticipated channel response of different anthropogenic activities based on Wallick et al. (2007) and several other studies in Table 5.

The major human drivers of channel change in the case of the Sharda River comprise massive deforestation in a short span of time, and expansion of agriculture and dams in the upper reaches. Comparison of our finding of increased instability, widened channel, decreased sinuosity, increased braiding intensity, and mystifying migrations, with the list of possible impacts (Table 5) suggests that the principal cause of the observed dynamics in the case of the Sharda River is deforestation and intensive agriculture, and other drivers appear to contribute minimally. Wide-ranging land conversion and deforestation after the 1950s especially in the upper reaches of the Sharda River on Nepal side must be accelerating bank erosion. The considerable runoff and sediment being produced as a result of heavy seasonal rainfalls get quickly and effectively transported to the river system downstream and are causing disastrous flooding on the Indian side. The altered flow regime is initiating and promoting abrupt channel changes and fostering the river to adopt a dramatically different style of evolution. The other possible drivers (i.e., dams) do not seem to contribute much to channel changes and probably has been playing a secondary role in changing flow regime. However, the land management authorities have been complaining about instantaneous release of water from the dams that cause more catastrophic flooding.

Table 5 River channel response to anthropogenic disturbance

Land-use change	Hydrological and geomorphic response	Studies
Deforestation/intensive agriculture in upper reaches	Bank erosion; increase of sediment supply; channel instability; channel widening; increase of migration rate and length; indeterminate avulsion frequency; increase of flood risk	Zimmerman et al (1967), Kondolf et al. (2002), Simon and Darby (2002), Murray and Paola (2003), Liébault et al. (2005), and Assine (2005)
Dam construction	Reduction in discharge; decrease in sediment supply; channel narrowing; change from braiding to meandering; decrease migration rate and avulsion frequency; change in shape and course of river during high discharge	Marston et al. (1995), Surian (1999), Larsen and Greco (2002), Uribelarrea et al. (2003), and Siddiqui et al. (2004)
Urbanization	Increase in magnitude and frequency of peak flow; decrease in sediment supply channel degradation; channel widening; accretion downstream	Trimble (1997) and Poff (2002)
Reforestation	Decrease in sediment supply and runoff; channel narrowing; change to meandering pattern; incision; new terrace level	Keesstra et al. (2005) and Beguería et al. (2006)

The question of the real cause of increased flooding in northern India has always resulted in impassioned debates among scientists, journalists, and politicians. The line of thinking regarding the impact of human activities in the Himalayas on the hydrological processes in the lowlands has increasingly been questioned. The majority of soil conservationists and watershed managers working in the Nepalese Himalayas and especially in the Indian lowland believe that the increased intensity and frequency of flooding, widespread erosion, and mass wasting throughout the Nepal are at least partly the result of anthropogenic activities (Kollmansperger 1978/79; Brunsden et al. 1981; Caine and Mool 1982; Valdiya 1985; Carson 1985; Garde and Kothyari 1987; Wells and Dorr 1987; Alexander 1989; Haigh et al. 1990; Froehlich and Starkel 1993; Rawat and Rai 1997; Joshi et al. 1998; UNEP/ISRIC 1990; Wasson 2003; Kale 2005). However, mainly in the scientific community, the "theory of Himalayan degradation" has not been accepted fully (Pearce 1986; Ramsay 1987; Ives 1987; Hamilton 1987; Ives and Messerli 1989; Messerli et al. 1993; Hofer 1993; Messerli and Hofer 1995; Hofer and Messerli 2006). The authors of these studies believe that the relationship between upstream activities and downstream damages is an assumption based on short-term series of measurements, a few experimental plots or case studies. At the large scale of the Himalaya–Ganga system, it has not been possible to find a significant correlation between human activities in the mountains (e.g., forest removal) and catastrophes on the plains (e.g., floods). Thus, the impacts of mountain deforestation on hydrological systems seem to be a question of scale and should not be generalized regionally (Ives and Messerli 1989). Furthermore, the theory may well reflect political and institutional influence, because the Ganga is an international river system (Chalise 1986; Haigh et al. 1990). Thus, a lot of questions about the effect of forest removal in the highlands on flooding in the lowlands remain open and need to be further explored, provided the availability and accessibility of data improve in the future (Hofer 1993).

Conclusions

The Sharda River creates and maintains ecologically diverse remnant patches of the rare *Terai* ecosystem in Dudhwa Tiger Reserve, India. The present study amply indicates that the Sharda River has undergone changes in 24 years between 1977 and 2001 and that its equilibrium is being disturbed continuously. The significant changes correspond to increased instability in terms of increasing number of neck cut-offs and consistent occurrence of avulsions in subsequent shorter periods, increased channel area (8 %), decreased sinuosity (15 %), increased braiding intensity, and confusing abrupt migrations. The Sharda River has migrated toward the east with its west bankline being more unstable. The maximum channel shifting was approximately 2.5 km in all the assessment periods. The altered dynamics is making the future of critical wildlife habitats in KWS and NKFD precarious and is causing huge economic losses. Extensive deforestation and expansion of agriculture since the 1950s in the catchment area are presumed to have severely disturbed the equilibrium of the Sharda River.

Floodplain management plan is the need of the hour for the Sharda Basin which could guarantee the conservation of the river and adjacent ecologically important wildlife habitats while minimizing risk to the inhabitants and supporting sustainable development of the floodplain. The present study provides a strong scientific foundation for understanding channel changes in the Sharda River and would serve as a valuable instrument for developing sound management plan and revising restoration schemes.

Acknowledgments This research was conducted at the Wildlife Institute of India (WII) with field support from officers and field staff of Dudhwa Tiger Reserve, Uttar Pradesh, India. Funding was provided by the Ministry of Environment and Forests (MoEF), Government of India for the project: WII-MoEF-National Natural Resource Management System. Thanks are due to Mr. P.R. Sinha, former Director, WII and Dr V.B. Mathur, Dean, Faculty of Wildlife Sciences, WII for encouragement and support. Thanks to Dr. Ambica Paliwal and Mr. Kumaran Sathasivam for proof reading. Special thanks are due to Messrs. Mohd. Ahsan; M.P. Singh; and P.P. Singh, senior officials of the Uttar Pradesh Forest Department for their help with field logistics. Thanks are also due to Dr. Molly Pohl-Costello and other anonymous reviewers for their helpful comments.

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