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Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland

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ABSTRACT

Hydrological and sediment transport characteristics for the Kosi basin, which covers parts of Nepal and India, were analysed to understand the spatiotemporal variability of the hydrology and sediment dynamics of the Kosi basin and its implications for flood hazard and sediment dynamics. The study revealed that ~56% of the discharge at Chatara (where all major tributaries of the Kosi meet) is contributed from the western part of the basin even though this constitutes only 34% of the total basin area. In contrast, the central and eastern parts of the basin constitute 57% and 8% of the basin area but contribute ~38% and ~16% of the discharge at Chatara, respectively. The contribution of sediment load at Chatara from the different tributaries of the Kosi River also shows a similar pattern. Of a total of ~100 million tonnes of the annual sediment load at Chatara, ~56% is transported from four tributaries: the Indrawati, Bhote Kosi, Tama Kosi (all draining from the west), and Tamor. The remaining ~44% is transported by other tributaries upstream of Chatara, the most important being the Arun, Dudh Kosi, and Sun Kosi. Sediment budgeting in this study, based on annual sediment load data, suggested that ~20 million tonnes of sediments are deposited between Chatara and Birpur annually. This study also found that ~53 million tonnes of sediments are being accommodated between Birpur and Baltara annually. Sediment dynamics in the Kosi basin emerges as the most important river management issue, and this is closely linked to channel instability and frequent flooding in the alluvial plains.

1. Introduction

Several studies have been carried out globally to develop strategies for sustainable basin management using hydrology, hydraulics and sediment transport; assessment of spatial and temporal variability of river discharge; channel dynamics; sediment yield; and sediment–fixed nutrient export (Chen et al., 2001; Mishra, 2008; Abraha, 2009; Greimann et al., 2011; Hooning, 2011; Zaharia et al., 2011). The Kosi (also known as Koshi) River drains through the high mountains of China and Nepal and then debouches into the alluvial plains of northern Bihar in India. The Kosi has been a problematic river over the last several decades owing to its extremely dynamic channels and frequent flooding (Gole and Chitale, 1966; Wells and Dorr, 1987; Sinha and Jain, 1998; Chakraborty et al., 2010). Previous research (e.g. Dixit, 2009; Sinha, 2009a,b; Sinha et al., 2013, 2014) has clearly established that the problems of channel instability and flooding have been aggravated in recent years. These were primarily due to several interventions for water resource development including the embankments on both sides of the river completed in 1955–56, and a barrage at Birpur completed in 1963 (India-WRIS, 2016). Excessive siltation in the alluvial part of the Kosi River has resulted in 'superelevation' of the river bed in several reaches with respect to the adjacent floodplains (Sinha et al., 2014). This has not only significantly affected the longitudinal connectivity of the river through alterations in planform morphology but has also increased the flood risk enormously in these reaches through multiple embankment breaches and avulsions over the years (Sinha and Jain, 1998; Sinha, 2009a; Sinha et al., 2013, 2014). It is, therefore, necessary to understand the implications of sediment dynamics on river processes and associated hazards in the Kosi basin to develop effective river management strategies.

Previous analysis of the hydrological data for the Kosi River for the alluvial reaches in India focussed on flood hazard assessment (Sinha

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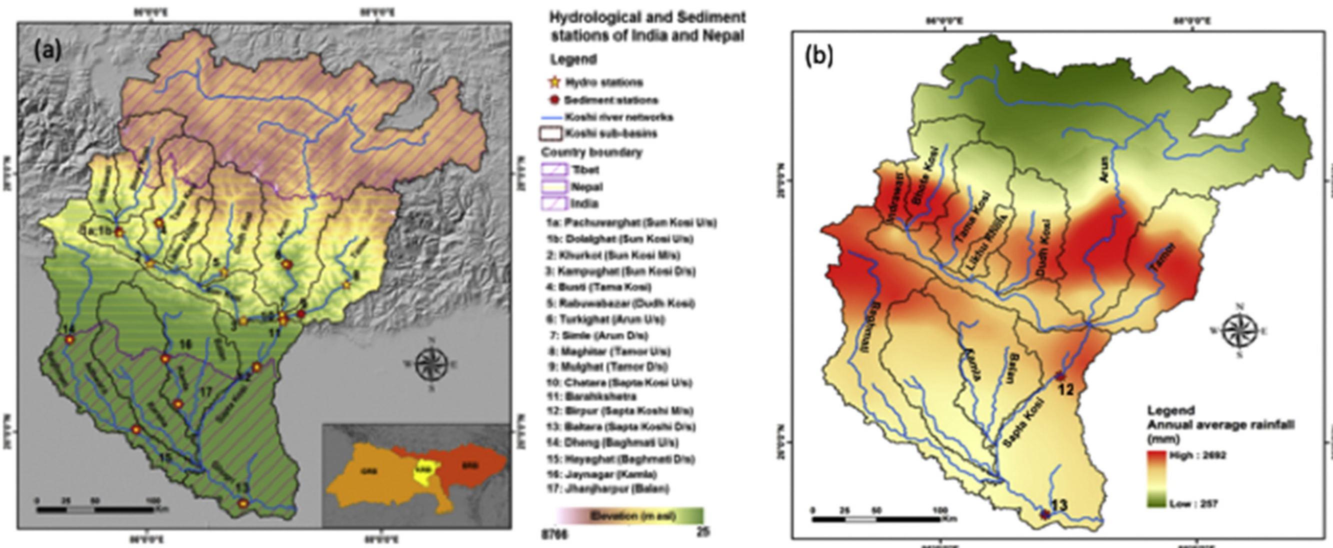


Fig. 1. (a) The study area showing hydrological and sediment stations of India and Nepal (Note: GRB, Ganges River Basin; BRB, Brahmaputra River Basin; KRB, Kosi River Basin). (b) Spatial variation in annual average rainfall in the Kosi basin (1951–2007).

and Friend, 1994; Sinha and Jain, 1998; Sinha et al., 2008). Similarly, hydrological modelling studies in the upstream mountainous catchment in Nepal have highlighted the impact of climate change on the hydrological regime of the Kosi River (Sharma et al., 2000; Bharati et al., 2016; Nepal, 2016) and upstream-downstream linkage through hydrological modelling (Panday et al., 2014; Nepal et al., 2014). This study presents a comprehensive analysis of the historical hydrological data for the entire basin in Nepal and India for the last 4–5 decades. We have used the standard methods of Flow Duration Curves (FDCs), Flood Frequency Analysis (FFA), discharge sediment relationships and sediment budgeting to derive a first-order estimate of sediment flux through the basin and to highlight its implications for river avulsion and flood risk.

2. Study area

The Kosi River drains the northern slopes of the Himalaya in the Tibet Autonomous Region and the southern slopes of the Nepal Himalaya before it finally enters the Bihar plains in India and meets the Ganga River (Fig. 1a). The mountain-fed Kosi River has a total basin area of 84,739 km^2 and spans a total length of 730 km up to Baltara (Gole and Chitale, 1966; Sinha and Friend, 1994). The Tibetan region of the Kosi basin comprises 22% of the total drainage area and is characterized by high elevation and flat plateau on the leeward side of the Himalaya with a large number of glaciers and glacier lakes (Bajracharya et al., 2007). About 40% of the drainage area of the Kosi basin lies in the Nepal Himalaya and is characterized by alpine and mountainous areas. The alluvial part of the Kosi basin in the Bihar plains in India comprises 38% of the total drainage area and comprises low elevation and flat plains with high population density.

The spatial variation in rainfall for the Kosi basin (Fig. 1b) shows that the mid-latitude region receives higher rainfall compared to the low and high latitudes (see Supplementary section for data used and analysis). The Tibetan region experiences very low rainfall as it lies on the leeward side of the Himalaya. Fig. 1b and Table 1 also show that the rainfall decreases from west to east of the Kosi basin in the Nepal Himalaya. The Pachuwarghat and Khurkot stations in the west show the highest basin average rainfall (~ 2900 mm) and Maghitar in the east shows the lowest value (1238 mm). A gradual decrease in rainfall from the Himalayan part of the basin in Nepal towards the alluvial reaches in Bihar is also noted.

All tributaries of the Kosi River originate from the high-altitude areas and, apart from rainfall, streamflow from glaciers, snow and permafrost contribute during the dry season (Singh et al., 1993; Bajracharya et al., 2007). The major drainage in the Tibetan region is marked by the tributaries of the Arun River flowing from the west as well from the east. In the Nepal Himalaya, the Kosi basin is drained by seven rivers: the Indrawati, Bhote Kosi, Tama Kosi, Dudh Kosi, Sun Kosi, Arun, and Tamor. The combined flow from these rivers reaches Tribeni through three major tributaries: the Sun Kosi from the west, the Tamor from the east, and Arun from the north (Sharma, 1977). Downstream of Tribeni, the river flows through a narrow gorge and then passes through the gauging station at Chatara. From this point, the Kosi is known as the 'Sapt Kosi' (literally, Seven Rivers), and eventually enters the alluvial plains of northern Bihar, India (Gole and Chitale, 1966).

Before debouching into the plains of northern Bihar, the flow of the Kosi is controlled by the Kosi Barrage at Birpur and is also embanked on both sides in the downstream reaches. A series of breaches in the embankment over the years have often resulted in large floods. One of the most recent breaches in the eastern embankment occurred at Kusaha in Nepal, 12 km upstream of the Kosi Barrage, on 18 August 2008. This resulted in a major shift of the Kosi River by ~120 km eastward, and globally, it was one of the greatest avulsions in a large river in recent years (Sinha, 2009a; Chakraborty et al., 2010; Sinha et al., 2014).

3. Data and methods

3.1. Discharge and sediment data

Discharge and sediment data at various stations in the Kosi basin falling in the Nepalese and Indian territory were obtained from Department of Hydrology and Meteorology, Nepal and the Central Water Commission (CWC), India respectively (see details in Supplementary Tables 1 and 2). The Kosi basin lacks continuous records of hydrologic data over a long period and there are gaps and inconsistencies in the available data from different stations. An averaging method was used to fill the data gaps, and Flow Duration Curves (FDC) to check the consistency of discharge data as well as to analyse the flow characteristics of different tributaries of the Kosi. Double Mass Curves (DMC) were also prepared to check the relative consistency and homogeneity of gauge stations within the same basin. Our analysis suggests that the discharge and sediment data are generally consistent (see Supplementary section for details).

Table 1
Rainfall and discharge characteristics of gauging stations in the Kosi basin.

River	Station	Catchment area upstream of the station (km^2)	Average rainfall at respective stations (mm/year)	Average annual discharge (m^3/s)	Q_{50} (50% dependable flow in m^3/s)	Q_{90} (90% dependable flow in m^3/s)
Sun Kosi*	Pachuwarghat	4842	2900	200	89	49
Sun Kosi	Khurkot	10,000	2929	469	204	93
Sun Kosi	Kampughat	17,600	2670	864	NA	NA
Tama Kosi	Busti	3088	2644	150	40	18
Dudh Kosi	Rabuwabazar	3717	2866	200	87	34
Arun	Turkighat	27,779	1400	456	228	101
Arun	Simle	30,380	2525	580	334	206
Tamor	Maghitar	4391	1238	249	102	45
Sapt Kosi	Chatara	52,730	2030	1545	681	323
Sapt Kosi	Barahkshetra	52,735	2030	1559	NA	NA
Sapt Kosi	Birpur	54,089	2041	1452	583	265
Sapt Kosi	Baltara	84,739	2103	2256	2430	420

* Downstream of the confluence of Indrawati and Bhote Kosi.

3.2. Discharge data analysis

Monthly average discharge data were used to generate the hydrographs for each station along the Kosi River and its major tributaries. Flow duration curves (FDC) were plotted using discharge on a logarithmic scale as the ordinate, and percentage of time discharge exceeded on a probability scale as the abscissa. Annual peak discharge data were used for Flood Frequency Analysis (FFA) to compute flood quantiles and corresponding prediction uncertainties at return periods of 2.33, 10, 50, and 100 years using Gumbel distribution. The Chi-square (γ^2) test was carried out to ascertain the goodness of fit of the Gumbel distribution.

The ratio between the peak discharge and mean annual flood (Q_{max}/Q_{av}) was used to characterize annual variability in the magnitude of the flood discharge in response to precipitation, temperature, evapotranspiration, and drainage basin characteristics (Beckinsale, 1969). Annual variability in the discharge was assessed from the ratio of maximum to minimum discharges (Q_{max}/Q_{min}).

3.3. Sediment load data

Suspended sediment load data for different stations were used to generate sediment-discharge rating curves (SDRCs) using the power law function (Eq. (1)), which describes the average relation between discharge and suspended sediment concentration or load for a certain location (Walling, 1974, 1978):

$$C_s = aQ^b \quad or\ Q_s = aQ^b \tag{1}$$

where C_s is the suspended sediment concentration (mg/l), Q is streamflow rate/river discharge (m^3/s), and Q_s is suspended sediment load (tonnes/day). The exponents α *and* β are site-specific constants or rating coefficients (Isik, 2013) related to basin characteristics such as runoff and relief, and represent the measures of soil erodibility and erosivity of the river, respectively (Rannie, 1978; Thomas, 1988).

For this study, the SDRCs were generated for four stations namely, Barahkshetra (1948–61), Chatara (2003–08), Birpur (2002–08) and Baltara (1990–98). Since suspended sediment load data at different stations are limited and fragmentary (see also Supplementary Tables 1 and 2), we selected the dataset for generating SDRCs for time windows when continuous sediment and discharge data were available with a common data measurement frequency (i.e., monthly basis). The relationship between discharge and suspended sediment load was considered to be consistent over the selected measurement period (Asselman, 2000).

The sediment budget between two stations along the same channel was defined (Eq. (2)) to provide an account of the sources and disposition of sediment as it traveled from its source to its outlet in the drainage basin (Reid and Dunne, 1996):

$$I = O + \Delta S \tag{2}$$

where I is input, O is output, and ΔS is the change in storage.

The sediment load data at different stations for the period 1980–2010 were analysed primarily to understand sediment dynamics across the basin, and to obtain a first-order estimate of the volume of sediment accumulating in the channel belt between a pair of stations. For sediment budgeting, average annual sediment load (MT/year) was calculated for all sediment stations. Since sediment data were not available for the same period, we have used the average annual sediment load contributed from all tributaries in the mountainous and alluvial parts.

4. Results and analysis

4.1. Discharge characteristics of the Kosi river

4.1.1. Hydrographs of the Kosi and tributaries

Hydrographs for the downstream stations (e.g., Baltara) had comparatively higher ordinates than those of the upstream stations, except in situations when the water was abstracted upstream of a station (e.g., Birpur-Chatara and Turkighat–Simle) (Fig. 2). Khurkot lies at the confluence of the tributaries on which Busti and Pachuwarghat are located and, therefore, it shows higher values of monthly discharges. The stations that do not fall along the same stream may have different catchment characteristics and hence different discharge patterns. The Pachuwarghat, Rabuwabazar and Maghitar stations show broad and low peak hydrographs with a low rising limb, as these catchments are elongated in shape with high slope angles and low drainage density. In contrast, Chatara, Birpur and Baltara stations show high peak and narrow hydrographs with pronounced rising limbs, representing an increase in the discharge due to storage in the catchment area as well as in the channels. These sub-catchments have low to very low slopes and high drainage density.

4.1.2. Flow duration curves (FDCs)

Fig. 3 shows the FDCs for all discharge stations in the Kosi basin. Pachuwarghat, Busti, Khurkot, and Rabuwabazar are the discharge stations that contribute at Chatara from the west of the Kosi basin. Turkighat, Simle, and Maghitar are the stations that link the eastern part, including the Arun River basin from the north. Table 1 shows the Q_{50} (flow available for 50% of the time) and Q_{90} (flow available for 90% of the time) values for all stations. As expected, the Q_{50} and Q_{90} values in a stream increase downstream, except for the reach between Chatara and Birpur. This deviation is attributed to the diversions at Birpur through eastern and western canals to irrigate nearly 9000 km^2 of land in India and Nepal. The FDC for the most downstream station, Baltara, is much higher than the FDC of the upstream stations of Chatara and Birpur because of its large catchment area. Similar

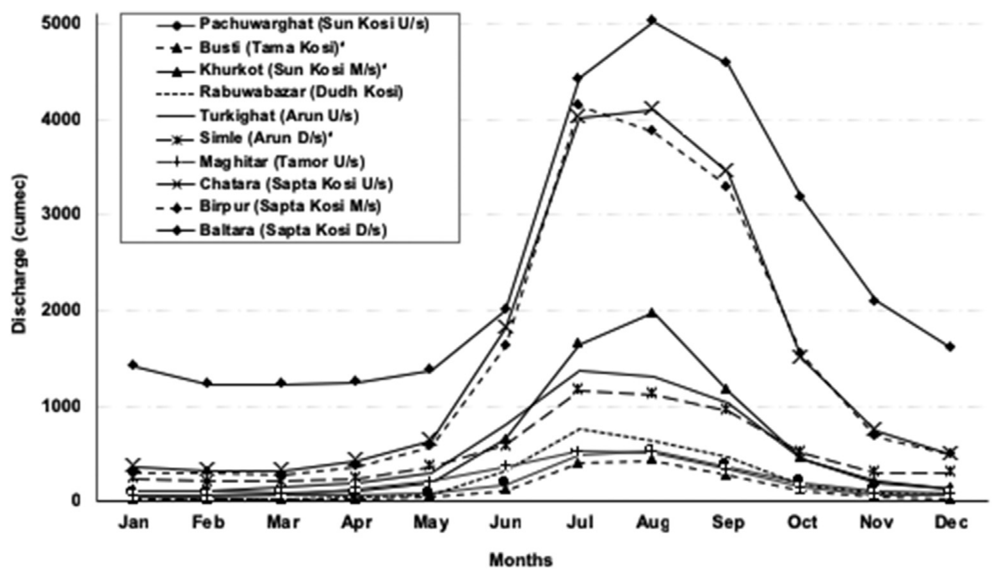


Fig. 2. Hydrograph for all discharge stations in the Kosi basin for the period 2003–2007 (Kampughat and Barahkshetra were excluded because data were not available for the selected duration); Busti, Khurkot, and Simle have data for the period 2003–2006 only. U/s, upstream, M/s, midstream, D/s, downstream.

explanations can be given for the pairs of FDCs for Turkighat–Birpur, Maghitar–Chatara, and Pachuwarghat–Chatara.

The Pachuwarghat, Busti, Khurkot, Rabuwabazar, Maghitar, Chatara and Birpur showed FDC with steep slopes throughout. This suggested highly variable flows that are largely derived from direct runoff from catchments that were dominated by low permeability lithologies. The FDCs for Baltara and Simle were relatively flatter, and this was attributed to the significant surface or groundwater storage and permeable catchment that tended to equalize the flow (Searcy, 1959; Liucci et al., 2014). The FDCs for Turkighat, Simle (Arun), and Baltara (Sapt Kosi) had flat peaks in the upper part (high flows) as compared to others. This suggested that the high flows of these streams came largely from snowmelt or through flood regulatory storage. In the case of Baltara, large floodplain storage (Searcy, 1959) may also have had a role. The lower end of the FDC is valuable for understanding the effect of geology on the groundwater runoff to the stream. The steep lower ends of the FDCs of Busti, Khurkot, Rabuwabazar, Birpur, and Baltara stations indicated that they did not have any perennial storage. In contrast, the FDCs of Pachuwarghat, Simle, Turkighat, and Chatara stations reflected considerable perennial storage.

4.1.3. *Flood Frequency analysis (FFA)*

Fig. 4 shows the results of FFA, and Table 2 presents the peak discharges and corresponding uncertainties in the estimates for 2.33, 10, 50 and 100 years of return periods. For the data following Gumbel distribution, the mean annual flood corresponded to the return period of 2.33 years (Leopold et al., 1964). Except for Barahkshetra, the estimates of peak discharges for the same return period for the downstream station were relatively higher than those for the upstream station along the same tributary. They also showed a strong dependency on lithological characteristics, catchment area and source of runoff generation.

Estimated peak floods of Maghitar and Rabuwabazar for all return

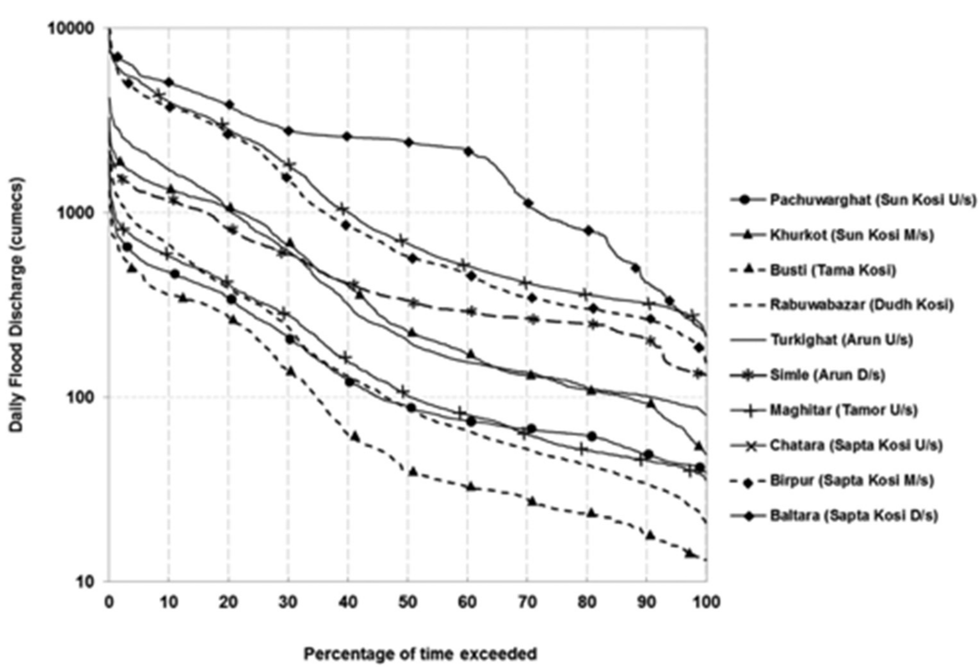


Fig. 3. Flow duration curve for various discharge stations in the Kosi basin plotted on a log-probability scale. U/s, upstream, M/s, midstream, D/s, downstream.

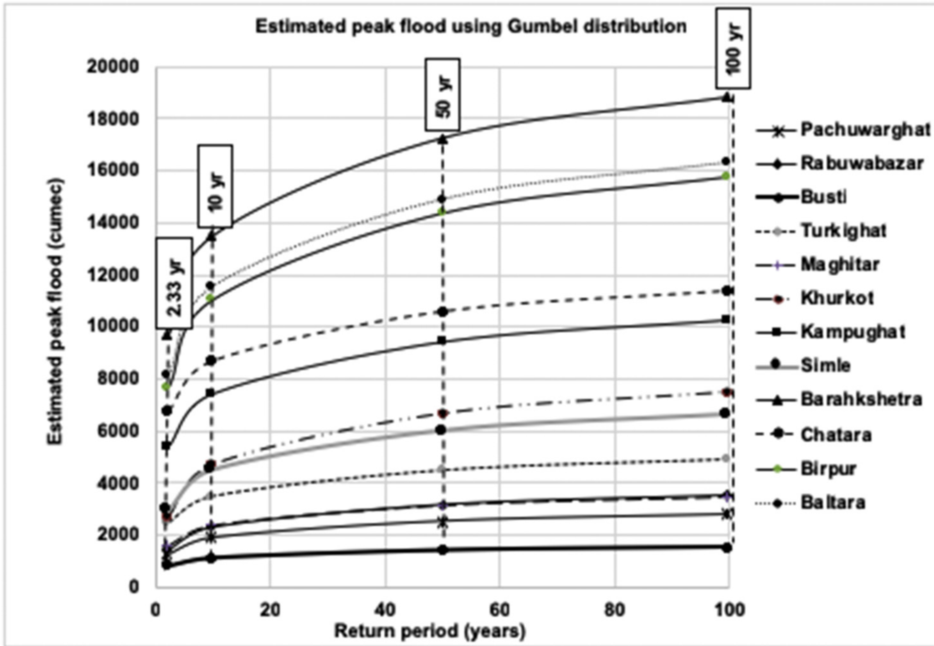


Fig. 4. Estimates of peak floods for different return periods based on Gumbel distribution.

periods were very close. The rate of change in the estimated peak floods showed a similar trend for the upstream stations such as Pachuwarghat, Rabuwabazar, Turkighat, Maghitar and Chatara. The trends for the downstream stations – Birpur and Baltara – were similar, but differed from those of upstream stations. Busti had the lowest peak flood, followed by Pachuwarghat, Rabuwabazar in the west, and Maghitar in the east. These regions are dominated by low permeability lithology, smaller catchment areas and steep slopes, which indicate that most flows (rainfall, glacial melt) lead to direct runoff (Anderson, 1957; Benson, 1962; Nash and Shaw, 1966). Simle had higher values of peak floods compared to the upstream station at Turkighat (both located along the Arun), and the flows were largely contributed to by glacial melt. Khurkot also showed higher peak discharge values compared to the upstream stations (Pachuwarghat and Busti). Chatara and Kampughat have large permeable catchments and extensive mainstream lengths, resulting in increased travel time for the direct runoff. As the river flows through a deep gorge near Barahkshetra, it shows a higher flood peak as compared to Birpur and Baltara, which lie in the piedmont area and alluvial plains, respectively.

4.1.4. Discharge variability and flood magnitude

Fig. 5(a–l) plots discharge variability (Q_{max}/Q_{min}) versus flood magnitude (Q_{max}/Q_{av}) for all stations. For all plots, the slope was positive suggesting that floods of higher magnitude (Q_{max}/Q_{av}) will also have higher discharge variability (Q_{max}/Q_{min}). Rabuwabazar showed high values for both flow variability and flood magnitude, followed by Khurkot and Maghitar. The plots for the Pachuwarghat and Barahkshetra stations showed the highest slopes with the highest coefficient of determination (0.82 and 0.94 respectively) amongst all stations. The rivers associated with these stations traverse the mountainous areas characterized by orographic rainfall that is manifested in high discharge variability as well as by high flood magnitude. The Busti, Kampughat, Turkighat, Birpur, Simle and Chatara stations showed low flood magnitude as well as flood variability, Chatara being the lowest with the least coefficient of determination (0.37). Baltara had the lowest rate of increment in flood magnitude with reference to flow variability. This is attributed to the location of this station in the most downstream part of the tropical basin, and to flow contributions from areas occupying more than one climatic zone. These observations indicate significant spatial variability in the flooding characteristics across the Kosi basin as a function of the geomorphic setting.

Table 2
Results of Flood Frequency Analysis.

Discharge Stations	Return period (T)							
	T = 2.33 years		T = 10 years		T = 50 years		T = 100 years	
	X_T (m³/s)	ΔX_T (m³/s)	X_T (m³/s)	ΔX_T (m³/s)	X_T (m³/s)	ΔX_T (m³/s)	X_T (m³/s)	ΔX_T (m³/s)
Pachuwarghat	1325	41	1934	98	2537	161	2791	188
Khurkot	2759	69	4726	157	6668	256	7489	298
Kampughat	5410	131	7436	310	9437	509	10,283	594
Busti	849	11	1135	25	1417	40	1537	47
Rabuwabazar	1185	82	1545	189	1900	308	2051	359
Turkighat	2464	269	3501	627	4527	1026	4960	1198
Simle	2985	98	4508	233	6013	383	6649	447
Maghitar	1646	246	2409	597	3163	985	3481	1151
Chatara	6695	84	8751	193	10,782	315	11,641	368
Barahkshetra	9923	1026	15,395	2309	20,801	3752	23,087	4373
Birpur	7711	1253	11,070	3165	14,389	5265	15,792	6165
Baltara	8153	726	11,551	1652	14,908	2691	16,328	3138

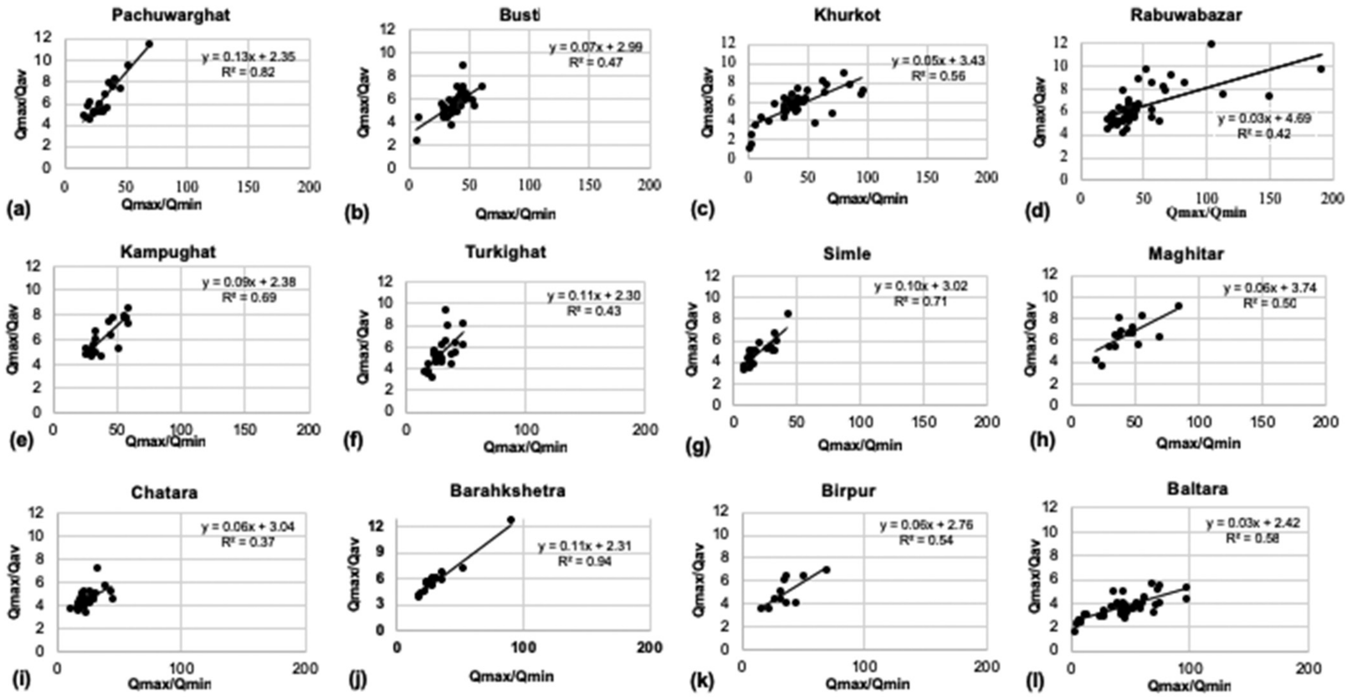


Fig. 5. (a–l). Flood magnitude versus flow variability for all discharge stations in the Kosi basin.

4.2. Sediment analysis

4.2.1. Discharge-sediment relationship

Sediment load and discharge data from July 2002 to November 2008 were analyzed to obtain SDRCs for the Barahkshetra, Chatara, Birpur (downstream of the Kosi Barrage), and Baltara stations (Fig. 6a–d). High β values for the SDRCs for Barahkshetra (2.23), Chatara (1.99) and Birpur (2.11), and a fairly low value for Baltara (1.18) indicated significant spatial variation in the erosive power of the river (Knighton, 1984) and dominance of sand and silt-sized sediments that require more power to transport (Asselman, 2000). Fig. 6 also shows a rising trend in rating curve for all stations, attributed to an increase in stream power and sediment transport capacity as discharge increases. However, the values of α were low for Chatara, Barahkshetra, and Birpur but very high for Baltara (Fig. 6). This reflected spatial variation in erodibility of soils, and high values at Baltara suggested the availability at this location of sediments that could be easily eroded and transported (Peters-Kümmerly, 1973; Morgan, 1995). Our analysis

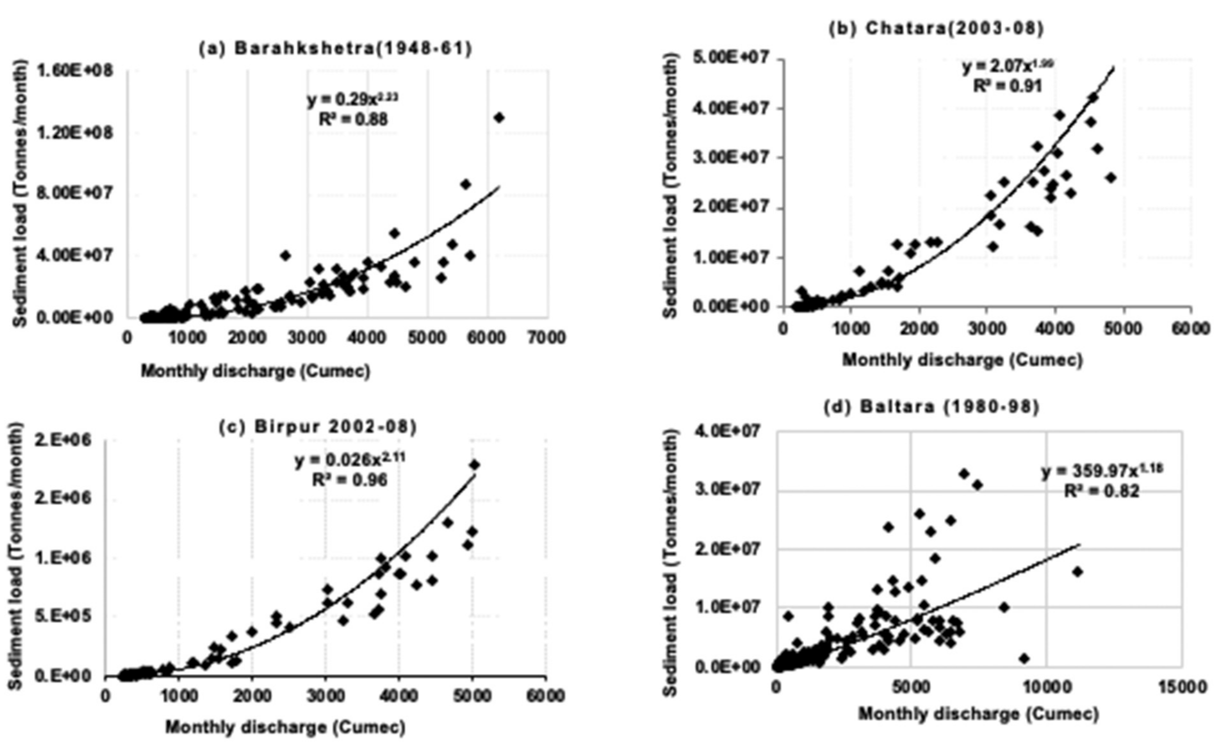


Fig. 6. Rating curves for monthly sediment load and discharge for (a) Barahkshetra (b) Chatara, (c) Birpur, and (d) Baltara.

Table 3
Annual average sediment loads and average annual discharges at sediment stations.

Sediment stations (measurement period)	River	Catchment area upstream of the station, A (km^2)	Average annual discharge, Q_{av} (m^3/s)	Average annual sediment load (Q_s) (MT/year)	Specific sediment load, Q_s/A ($T/y/km^2$)	Specific discharge, Q_{av}/A ($m^3/s/km^2$)
Dolalghat* (near Pachuwarghat) (2005–07)	Sun Kosi	4842	200	30	6200	0.041
Busti (2006–08, 2010)	Tama Kosi	3088	150	10	3240	0.049
Mulghat* (2004–05)	Tamor	5892	334	16	2720	0.057
Chatara (2003–10)	Sapt Kosi	52,730	1545	101	1915	0.029
Barahkshetra (1948–89)	Sapt Kosi	52,735	1559	94	1780	0.030
Birpur (2003–08)	Sapt Kosi	54,089	1452	81	1500	0.027
Baltara (1980–89, 93–97)	Sapt Kosi	84,739	2256	43	510	0.027
Dheng**	Baghmati	3790	156	10	2640	0.041
Hayaghat**		8440	189	7	830	0.022
Jaynagar**	Kamla-Balan	2131	66	10	4690	0.031
Jhanjharpur**		2945	68	8	2720	0.023

* Dolalghat and Mulghat are two stations where no flow data are collected and only sediment data for a limited period are available. The average discharge of the nearby discharge station (Pachuwarghat), therefore, was used for Dolalghat. For Mulghat, the area averaging was done using the data for the Maghitar station, which lies on the same river (Tamor). MT, million tonnes.

** Compiled from Sinha and Friend (1994) and Sinha et al. (2005).

suggests, therefore, that the Kosi behaves as a supply-limited system at Chatara, Barahkshetra, and Birpur, but as a transport-limited system at Baltara. This is in contrast to the rivers draining the western Ganga plains where most rivers are supply-limited (Roy and Sinha, 2017).

Table 3 lists the catchment areas with average annual discharges, average annual sediment loads, sediment yield (sediment load per unit of catchment area) and specific discharges (discharge per unit area) at different stations. An increase in the average annual discharge from upstream to downstream was noted as a function of the catchment area of the respective stations. The Dolalghat, Busti and Mulghat stations showed high specific discharges compared to the other stations. This is because these three stations lie in the High Himalayan region and have a highly dissected terrain with high longitudinal slopes. Lower specific discharge at Chatara and Barahkshetra was due to limited contributions from the upstream Tibetan part that is a low precipitation zone because of the rain shadow effect. Downstream of Chatara/ Barahkshetra, a decreasing trend of specific discharge is noted.

Table 3 shows that the sediment yield decreases from upstream to downstream. Sediment yield was plotted against annual average discharge and specific discharge (Fig. 7a, b) at all stations. As average annual discharge increases, specific sediment load decreases (Fig. 7a), and this can be explained as the drainage area effect (Latrubesse et al., 2005). Table 3 and Fig. 8b also show that, as specific discharge increases, sediment yield also increases. Exceptions to this trend are noted for two pairs of stations: Dolalghat–Busti, and Busti–Mulghat. The specific sediment load at Dolalghat (which has a major contribution from Bhote Kosi) was more than that at Busti (Tama Kosi) but specific discharge at Dolalghat was less than that at Busti. Similarly, the specific sediment load at Busti was higher than that at Mulghat (Tamor), but specific discharge at Busti was less than that at Mulghat. It is argued that these variations are primarily related to sediment connectivity of the individual basins, which governs the efficiency of sediment transfer (Harvey, 2001). Sediment connectivity analysis for the upper Kosi basin has shown that the Bhote Kosi sub-basin is highly connected followed by the Tama Kosi and Tamor sub-basins (Mishra et al., 2019) and this is manifested in sediment yield from these sub-basins.

4.2.2. Sediment budgeting

Chatara (Fig. 1) is situated immediately downstream of the confluence of the three major tributaries of the Kosi. Hence, the sediment load at Chatara represents the total sediment transported from the upstream sources (Fig. 8). Of the total sediment load at Chatara (101 MT/year, Table 3), 56 MT/year of sediment was transported from three basins: Indrawati and Bhote Kosi (Dolaghat), Tama Kosi (Busti), and Tamor (Mulghat). Presumably, the remaining 45 MT/year is transported by other tributaries upstream of Chatara, the most important being the Arun, Dudh Kosi and Sun Kosi (downstream of Dolaghat) for which no independent estimates were available.

It is important to note that the Chatara, Birpur and Baltara stations lie on the same stream, and hence, sediment budgeting was been done

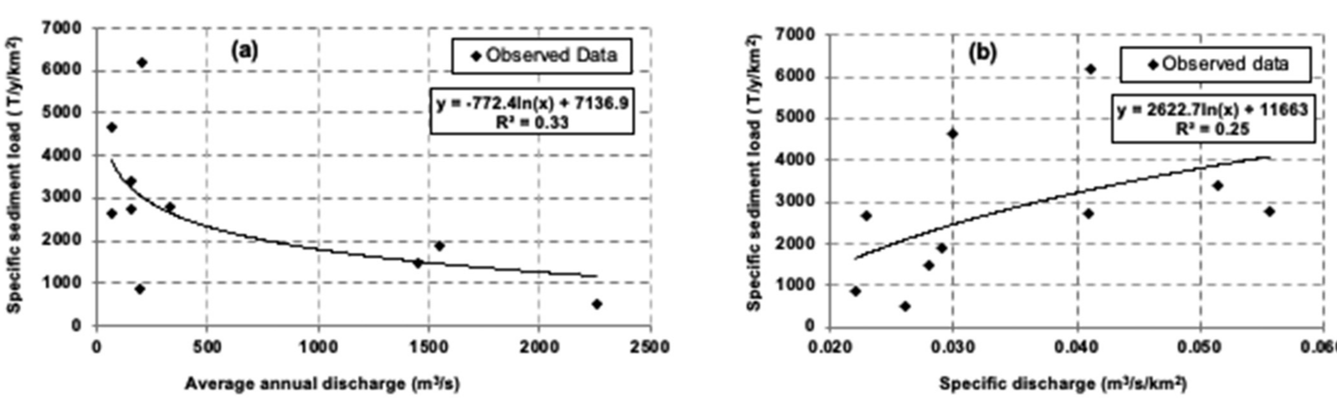
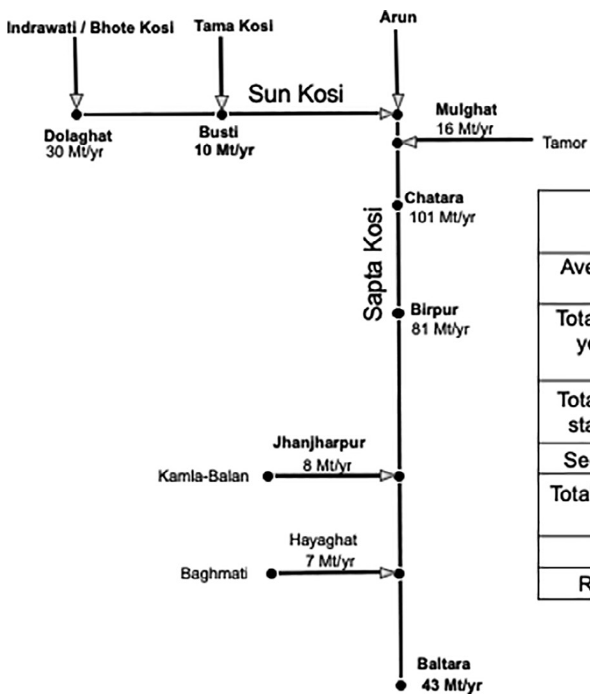


Fig. 7. Specific sediment load versus (a) annual average discharge and (b) specific discharge.



Parameters	Chatara-Birpur	Birpur-Baltara
Average sediment load between the stretch (Mt/yr)	(101-81) =20	(81+8+7-43) = 53
Total sediment mass deposition in 54 years (post embankment period) (million tonnes)	1080	2862
Total area of deposition between the stations (channel belt area) (km^2)	142	507
Sediment Density (fine sand) kg/m^3	2650	2650
Total sediment volume accumulated in 54 years m^3	408×10^6	1080×10^6
Sediment thickness (m)	2.87	2.13
Rate of sedimentation (cm/year)	5.31	3.94

Fig. 8. Sediment budgeting of the Kosi river system. Mt/yr, million tonnes/year.

only for this stretch. The inputs from two important tributaries of the Kosi in the alluvial reaches (the Baghmati and Kamla-Balan) were considered for the Birpur–Baltara stretch; these contributed 7 MT and 8 MT of sediments annually (Sinha and Friend, 1994). Fig. 8 shows that the annual sediment load at the upstream station at Chatara (101 MT/year) is higher than that at the downstream station at Birpur (81 MT/year), suggesting aggradation of 20 MT of sediments annually between these two stations. This may be attributed to the break in slope at Chatara and the presence of the Kosi Barrage at Birpur, which acts as a barrier to sediment transport and induces siltation upstream. Further, the total sediment input in the Birpur–Baltara stretch is much higher (96 MT/yr) than the sediment load measured at Baltara (43 MT/yr), suggesting a further deposition of 53 MT/year of sediment annually between Birpur and Baltara (also see Section 5.1). Such large scale aggradation is attributed partly to the barrage located just downstream of Birpur but mainly to the very low longitudinal slope (0.01–8.4°) between Birpur and Baltara.

5. Discussion

5.1. Hydroclimatic conditions and discharge contributions

Our analysis suggests that the Kosi basin has extremely variable hydroclimatic characteristics. Rainfall data (Table 1) suggest that Pachuwarghat and Maghitar have the highest and the lowest average annual rainfall respectively, and the difference is as great as 2400 mm over the entire basin (Fig. 1b). The mid-latitude region receives the maximum average rainfall, which increases from the west to the center and decreases towards the east. The rainfall distribution in the Kosi basin is clearly manifested in the discharge contributions at Chatara from different parts of the basin. Considering average annual discharges at Kampughat (Sun Kosi), Simle (Arun) and Maghitar (Tamor) as the sum total of contributions from western, central and eastern parts, respectively, it is noted that ~56% of the discharge comes from the western part only, even though this constitutes only 34% of the total basin area up to Chatara. In contrast, ~33% of the discharge comes from the central part (58% of the basin area), and only ~16% from the eastern part (~8% of the basin area up to Chatara).

5.2. Basin scale sediment dynamics and controls

Although sediment data for all stations do not correspond to the same period of observation, a first-order sediment budgeting provides important insights about sediment dynamics in the Kosi basin. It is estimated that more than ~40% of the total sediment load at Chatara (101 MT/yr) is contributed by the western tributaries: the Indrawati and Tama Kosi. The eastern tributary (Tamor) adds ~16% of the total sediment load at Chatara. The remaining ~44% of the sediment load is contributed by Arun, Dudh Kosi and Sun Kosi (after Dolalghat), from which no independent sediment load data are available.

The sediment budgeting in this study also provides a first-order estimate of total mass and volume of sediments being accumulated in the channel belt over the last few decades. Estimates for the last 54 years (post-embankment period) suggest that the total mass of sediments accumulated in the channel belt between Chatara and Birpur could be ~1080 MT, which translates to 408 million m^3 of volume, and this may have accumulated at a rate as high as 5.31 cm/year (see inset table in Fig. 7). The average thickness of sediments accumulated in the channel belt over the period of 54 years is computed as 2.87 m in this stretch. This is attributed to the relatively narrow channel belt (and a smaller area) available for sediment accommodation (i.e. 142 km^2 between the two stations). In contrast, the channel belt is much wider between Birpur and Baltara, and the available depositional area is almost five times the area between Chatara and Birpur. The barrage at Birpur also acts as a barrier to coarse and medium fractions of sediments. Taking the sediment load at Birpur – as well as contributions from the Baghmati and Kamla-Balan system – into account, the total sediment accumulation in the Birpur–Baltara stretch is very high (2862 MT), translating to ~1080 million m^3 of sediments. This is because of large channel widths in this stretch that can accommodate a large volume of sediments but results in lower sediment thickness and sedimentation rate (2.13 m, 3.94 cm/year, respectively). It is important to note, however, that the sediment thickness computed from this method assumes uniform sedimentation across the entire channel belt. In practice, the rate of sedimentation is extremely variable and is controlled by local slopes and hydrological conditions. Therefore, local sedimentation rates and thickness may be much higher, as reported in

Sinha et al. (2014)), where the river bed around Kusaha was estimated to be 2–3 m higher than the adjoining floodplain.

Table 3 also shows a decreasing trend of sediment yield at Dolalghat, Busti, Mulghat, and Chatara that clearly reflects the contributing area, but rainfall also plays an important role in mobilizing the sediments downstream. For example, a large part of the Arun lies in the mountainous Tibetan region where sediment production is high. This is demonstrated by a ^{10}Be-derived mean denudation rate of 1.44 mm/yr for the tributaries of the Arun draining through the Higher Himalaya compared to other tributaries of the Kosi draining through the Lesser Himalaya (~ 0.2–0.5 mm/yr) (Olen et al., 2015). However, the rainfall in the Arun basin is fairly low (Table 1), and therefore, total sediment transport is less. Further, the Tibetan part of the Arun also shows low sediment connectivity between the hillslopes and channel (Mishra et al., 2019) and this will also result in lower sediment yield. In contrast, the tributaries draining the middle Kosi basin not only produce large amounts of sediment but this is also mobilized downstream because of higher rainfall compared to the Tibetan region. Sediment transported from the hinterland is deposited downstream of Chatara because of a major topographic break, drastically reducing the slope and stream power. This occurs even though the mean discharge at Chatara (1545 m^3/s) is much higher compared to other stations.

It is important to understand the causal factors of such high sediment supply and aggradation in the Kosi basin for designing a sustainable sediment management strategy. Natural erosion in the Himalaya has been an important phenomenon and is probably higher than in most other mountain systems in the world (Ives and Messerli, 1990). It is well established that the Himalayan river basins are characterized by high annual rainfall resulting in high streamflow rates, steep slopes, and a young and fragile hinterland (Bruijnzeel, 1990; Ives and Messerli,1990). These factors limit the opportunity to store sediment, and a high rate of sediment transport is reflected in the basin output. However, there is significant spatial variability in sediment yield from different parts of the Kosi basin; this study suggests that sediment connectivity also plays an important role here (see Mishra et al., 2019).

Apart from the natural factors, human impact on the sediment yield may have been substantial in recent years because of large-scale developmental activities such as road construction in many parts of the basin falling within Nepal. In regions with high rainfall rates, steep terrain, and high natural erosion rates (similar to the Himalayan region), the relative impact of land use may be negligible. However, at this stage, it is not possible to separate the natural and anthropogenic contributions to the sediment flux in the Kosi basin.

5.3. Implications for morphodynamics, floods, and hydropower

The high sediment yield of the Kosi River has significant implications for the morphodynamics of the river and floods, particularly in the downstream reaches. The construction of embankments on both sides, and the Kosi Barrage has further aggravated the situation and channel siltation is now confined within the embankment. This has led to a decrease in the longitudinal gradient and an increase in cross-valley gradient, the ratio of which determines the avulsion threshold (Bryant et al., 1995; Mackey and Bridge, 1995). At many locations, large-scale aggradation has resulted in a ‘superelevated’ channel (Sinha et al., 2014), where the elevation difference between the channel bed and the surrounding floodplain is as much as 4–5 m. This often leads to channel instability and avulsions, the last major event being the 2008 avulsion at Kusaha following the breach in the embankment (Sinha, 2009a; Sinha et al., 2014; Majumder and Ghosh, 2018). This single event resulted in a maximum shift of ~ 120 km of the Kosi channel in the alluvial region for a few months, and also in a large flood affecting more than 3 million people in Nepal and northern Bihar.

The Kosi is often called the ‘sorrow of Bihar’, mainly because of its frequent and extensive floods and the migration that is often linked to them. It is important to note that since the construction of the embankments, most floods in the Kosi basin have occurred because of the breaches in the embankment rather than through overbank flooding. Nine breaches have occurred since 1963 on both eastern and western embankments, resulting in severe flooding (Mishra, 2008; Sinha et al., 2014). The latest breach in August 2008 at Kusaha, 12 km upstream of the Kosi Barrage, occurred at a relatively low water discharge (4,320 m^3/s) compared to the design discharge (28,500 m^3/s) of the embankment. This was attributed to the fact that the river was very close to the avulsion threshold at that point because of its superelevated position (Sinha, 2009a; Sinha et al., 2014).

Hydroelectric power projects have a designed power production capacity. This capacity depends on the discharge of the river and head at the turbine. The extent of erosion and deposition will change because of spatiotemporal variability in meteorological conditions, and to the hydrological and geomorphological characteristics of the basin. Landslides triggered by hillslope erosion, levee breach, and channel avulsion may result in partial or total abandonment of hydroelectric projects. A recent example is a major landslide in the upstream reaches of the Bhote Kosi (Jure landslide in 2014); this created a large dam upstream and a small hydroelectric power station downstream became defunct. Further, sediment-extruding mechanisms may be required during higher sediment transport so that the channel is not filled, or which prevent sediment from partially or fully entering the turbine.

The Kosi basin is considered to have significant hydropower potential and at least three multipurpose projects – the Kosi High Dam at Barahkshetra, the Tamor-I, and the Sun Kosi-Kamla Diversion project – have been under discussion (Thapa, 1993; Chinnaswamy et al., 2015). These projects have been conceived for flood and sediment control and for hydropower generation, and partially for irrigation. The high sediment yield of the Kosi and its tributaries is a major concern for all these projects (Nayak, 1996). The findings of this study will benefit hydropower projects by promoting an understanding of the spatial variability in sediment load at different catchments and the planning of an appropriate sediment control strategy. Similarly, the information on flooding characteristics, particularly on floods of different return periods, will be very useful in designing hydropower capacity and infrastructure.

6. Conclusions

The hydrological characteristics of the Kosi River and its tributaries show significant spatial and temporal variability. This first-ever compilation of all available data for water discharge and sediment load for the entire Kosi basin draining through Nepal and northern Bihar provides important insights about the influence of basin characteristics on flow and on sediment storage and transfer. Our analysis suggests that the western tributaries contribute ~56% of the total annual flows at Chatara, whereas the central and eastern parts add ~38% and ~16%, respectively. Further, ~40% of annual sediment load is contributed from the western tributaries, ~16% from the eastern tributaries, and the remaining ~44% from the central part of the Kosi basin. Discharge–sediment relationships suggest that the Kosi River is supply-limited at the upstream stations (Chatara and Birpur), but transport-limited at the downstream station (Baltara), leading to large-scale aggradation in the alluvial reaches. The embankments constructed on both sides of the river in 1955–1956 have constrained the river flow, and this has increased in-channel sedimentation significantly. Sediment budgeting from the study suggests that ~408 million m^3 of sediments may have accumulated between Chatara and Birpur and ~1080 million m^3 between Birpur and Baltara in the post- embankment period of 54 years. Such large-scale aggradation has resulted in ‘superelevated’ channels at several locations, leading to serious problems of channel instability and flooding. This study shows that sediment dynamics in the Kosi basin is one of the single most serious problems and is linked to several river-related hazards. Sediment management plans should, therefore, become an integral part of river management of the Kosi and its tributaries.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2018.12.051.

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