sustainability

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Sustainable Silt Management in the Lower Kosi River, North Bihar, India: Demand Assessment, Investment Model and Socio-Economic Development

S1: Methodology

Detailed planform mapping of the Kosi River between Chatara and Baltara was performed on a decadal basis for the years 1972, 1980, 1992, 2000, 2009, and 2016. The post monsoon satellite data used for this process are shown in Table S1a at a scale of 1:50,000 and all in-channel bars were8 mapped. The morphological units were extracted from the satellite images in a GIS framework and classified based on their location and origin, such as (a) mid-channel bars, occurring in the center of the channel, (b) lateral bars or side bars along the channel, and (c) point bars formed11 on the concave bends, (d) alluvial islands formed by aggregation and stabilization of some of the12 midchannel bars. To observe and quantify the subtle morphological changes in the river planform, the stretch of Kosi River between Chatara and Baltara was divided into 37 reaches of ~5 km length (Figure 3). Further, bar area (BA) which defines the depositional areas and channel area (CA), define the flow were measured within the channel belt (CB). The ratio BA/CA was used as an index to map aggradational hotspots in each reach normalized for channel area (Figure 4a). Based on the statistical distribution of the reach-wise BA/Ca, we have identified five classes of aggradation values using Jenks natural breaks classification method, (Jenks and Caspall 1971; Coulson 1987) (Figure 4c). To estimate the first-order sediment thickness and rate of deposition in the Kosi main channel for the post-embankment period, a short-term sediment budget was calculated from sediment data collected from stream gauging stations, i.e., from Chatara, Birpur, and Baltara for different water years were already discussed in the (Sinha et al. 2019). The estimated cumulative vertical thickness calculated on the channel belt area of deposition was derived from geomorphic maps. It is important to note that sediment volume estimation based on sediment load data between a pair of gauging stations as discussed above refer to long stretches along the river. In practice, river exhibit significant spatial variations in pattern and amount of sediment accumulation. The estimation of precise volume in each reach is not possible without close interval cross-sections of the river. Therefore, an integration of planform maps derived from repetitive satellite images and hydrological data can provide a first-order assessment of hotspots siltation in a long stretch of the river. Therefore, a first-order estimation the volume of sediments accumulated within the channel belt was calculated for each mapping year using sediment budgeting method. It was based on the bar area and an average height of sediments accumulated in the reaches of Chatara–Birpur and Birpur–Baltara.

Table S1. Data used for geomorphic mapping and planform dynamics.

Data type			Month/Year of Acquisition	Ground Resolution/ Scale
Satellites	**Sensors**	**Path/Row**		
Landsat 8	OLI	141/041 141/042	2016/1/26. 2016/1/3	bands 1-7 and 9: 30 meters, band 8: 15 meters, band 10, 11: 100 meters but resampled to 30 meters

Landsat 5	TM	141/041 141/042	2009/12/02	bands 1-5 and 7: 30 meters, band 6: 120 meters
Landsat 7	ETM+	141/041 141/042	2000/12/1 and 2000/12/30	bands 1-5 and 7: 30 meters, band 6: 60 meters, band 8: 15-meters
Landsat 5	TM	140/41 140/42	1992/11/17 and 1992/11/01	bands 1-5 and 7: 30 meters, band 6: 120 meters
Landsat 3	MSS	150/042	1980/01/18	bands 1-5 and 7: 30 meters, band 6: 120 meters
Landsat 1	MSS	150/042	1972/11/07	bands 4 - 7: 60 meters

Table S2. Potential solutions for silt management 41.

Sr No	Potential Solutions	Description
1	**Fencing**	
A)	Geotextile Silt Walls	Silt walls/fence are used on river embankments to protect the embankments from erosion, damage, and destruction.
2	**Agricultural Purposes**	
A)	Cultivation	Silty soil is usually more fertile than other types of soil; hence, it is good for growing crops. Silt promotes water retention and silty soil can be used as a replacement for loamy soil.
B)	Agricultural Use	The fine dredged material is used to supply organic content and nutrients to deficient soils to increase productivity. The fine materials also help to hold water and promote the retention of soil moisture needed by the crops.
C)	Produce Topsoil	Topsoil can be used to improve drainage in areas of a lawn or garden that floods.
3	**Landscape**	
A)	Gardening	Silty soil typically contains a lot of nutrients because it comes from river sediments. This is a good and common soil for gardening.
B)	Landscape Material	The fine dredged material can be used as a replacement of eroded topsoil, for which there is a high demand. It can further be added with organic wastes (such as dead leaves, dead wooden logs etc.) and bio-solids (such as animal manure or sewage sludge) and composted to more organic rich soil.
4	**Reclamation**	
A)	Land Reclamation	Dredged material can be used to reclaim the land disturbed and/or contaminated by industrial activities to a more natural condition/ minimizing the contaminants migration.
B)	Mine Reclamation	The silt material from dredging can be reused during mine reclamation to build up the land and make it suitable for vegetation growth.
5	**Embankment**	

A)	Usage of Silt for building / Repair of Embankments	Silt can be used as a fill material for building embankments. Also, damage to the embankment happens very frequently. To protect the embankment, it is suggested to deposit this silt on two sides of the embankment.
B)	Constructing roads on Embankments	Silt can be utilized in constructing roads on embankment, thereby, improving transport and connectivity of the city/state.
6	**Backfilling**	
A)	Road Construction	Sand/silt of the river can be used as fill material for constructing new roads, widening the road or increasing the height of the road. It can also be used in making paving blocks.
B)	Land Filling	Landfills require liners during construction, cover material during use, and caps when they are finally closed. Small particles, such as silt and clay, are ideal for low-permeability applications.
C)	Fill Material	It can be used primarily as a backfill material in large infrastructure projects, creation of habitat islands, building base for railway tracks, etc. where potential subsidence of backfill creates problems.
D)	Raising level of Houses	The silt can be utilized to raise the level of houses in villages living inside the embankment.
7	**Industrial Activities**	
A)	In ceramic Industry	Ceramic products like paving blocks, wall tiles, etc. can be made up with Kosi silt.
B)	Bricks & Compressed Blocks	Dredged material can be substituted as a raw material for manufacturing fired bricks for use in construction of buildings and other structures.
C)	Manufacturing of cement	Dredged sediments can also be used as replacement of raw material for manufacturing Portland cement

Table S3. Reach-wise calculation of bar area (BA), channel area (CA) and channel belt area (CB) of Kosi River from Chatara to Baltara during 1972-2016 in Lower Kosi basin.

	1972			**1980**			**1992**			**2000**			**2009**			**2016**			1972-2016	
Reach ID	**CA**	**BA**	**CB**	**CA**	**BA**	**CB**	**CA**	**BA**	**CB**	**CA**	**BA**	**CB**	**CA**	**BA**	**CB**	**CA**	**BA**	**CB**	Avg CA	Avg BA
WINDOW-I																				
1	4.17	17.04	21.21	4.52	13.65	18.17	2.48	10.47	12.95	3.69	6.39	10.09	3.32	5.62	8.94	3.38	6.15	9.52	3.59	9.89
2	5.08	23.57	28.66	5.77	19.98	25.75	3.75	13.32	17.07	4.74	8.49	13.22	3.21	11.14	14.35	3.82	11.25	15.07	4.39	14.62
3	7.22	20.24	27.46	6.26	16.91	23.17	5.14	9.07	14.21	6.33	10.28	16.61	6.72	9.59	16.31	5.58	10.52	16.10	6.21	12.77
4	8.04	18.87	26.91	8.94	14.33	23.26	4.74	4.77	9.51	6.37	9.06	15.42	10.56	12.15	22.72	6.76	12.80	19.56	7.57	12.00
5	8.50	23.30	31.80	6.76	20.67	27.44	4.70	5.45	10.15	3.88	9.15	13.03	5.03	10.99	16.02	6.53	13.51	20.04	5.90	13.84
6	7.90	13.88	21.78	5.01	11.82	16.84	4.25	8.53	12.78	3.58	11.30	14.88	4.86	12.13	16.99	7.49	14.36	21.85	5.51	12.00
7	5.62	13.54	19.16	3.91	11.43	15.34	5.40	7.89	13.29	5.27	11.37	16.63	5.50	11.85	17.34	7.30	16.43	23.73	5.50	12.08
8	8.21	13.07	21.28	4.85	9.00	13.85	8.00	7.05	15.05	5.66	11.07	16.73	6.34	9.21	15.56	5.84	10.28	16.12	6.48	9.95
9	6.40	15.64	22.04	4.56	23.49	28.05	6.36	26.78	33.14	4.38	29.45	33.82	3.86	30.14	34.00	7.03	29.49	36.51	5.43	25.83
10	9.99	25.10	35.09	4.48	32.02	36.51	6.27	31.12	37.39	5.80	33.88	39.68	4.60	31.90	36.49	7.87	30.27	38.14	6.50	30.71
11	7.71	26.39	34.10	5.37	29.50	34.87	5.97	33.45	39.42	5.55	27.67	33.22	3.50	27.34	30.84	6.78	24.01	30.79	5.81	28.06
12	6.98	25.39	32.37	3.61	29.44	33.05	6.62	25.47	32.09	7.06	26.71	33.77	5.83	24.49	30.31	5.85	24.72	30.57	5.99	26.04
13	7.83	24.39	32.22	4.36	29.13	33.49	6.03	27.78	33.81	7.89	26.71	34.60	6.88	27.02	33.90	7.62	26.17	33.79	6.77	26.87
14	6.73	31.28	38.01	2.86	35.57	38.42	5.81	25.33	31.14	7.11	34.28	41.38	6.98	32.61	39.59	11.72	32.79	44.51	6.87	31.98
15	7.62	36.76	44.38	3.34	37.59	40.93	4.98	27.67	32.66	6.44	34.94	41.38	7.01	29.55	36.56	5.59	29.84	35.43	5.83	32.72
16	5.45	42.82	48.26	3.36	36.03	39.39	6.48	21.93	28.40	7.06	30.57	37.63	7.11	30.64	37.75	5.90	32.84	38.74	5.89	32.47

17	5.39	25.55	30.95	3.30	29.23	32.53	4.89	17.38	22.27	7.44	18.54	25.98	4.82	25.95	30.77	6.86	23.77	30.63	5.45	23.40
18	6.45	21.90	28.34	2.82	28.93	31.75	4.96	14.74	19.69	5.26	21.64	26.91	4.21	21.82	26.03	5.92	18.99	24.91	4.94	21.34
19	6.84	31.97	38.81	4.61	27.65	32.26	5.94	9.24	15.19	6.34	24.56	30.89	5.36	20.88	26.25	4.92	27.73	32.65	5.67	23.67
20	5.76	17.84	23.60	4.03	21.19	25.22	5.11	20.05	25.16	4.81	23.58	28.39	5.16	19.89	25.04	5.15	13.54	18.68	5.00	19.35
21	4.24	7.67	11.91	2.06	22.47	24.54	5.58	13.89	19.47	4.75	16.68	21.44	3.64	8.50	12.14	4.37	7.81	12.18	4.11	12.84
22	4.14	5.95	10.09	2.82	18.65	21.47	4.63	16.75	21.37	4.20	17.43	21.63	2.88	4.47	7.35	4.29	9.73	14.02	3.83	12.16
23	5.51	13.23	18.74	2.60	18.11	20.72	3.78	2.22	6.00	3.53	9.01	12.53	3.15	10.37	13.52	5.03	5.87	10.90	3.93	9.80
24	3.20	5.02	8.22	1.44	7.77	9.21	2.66	1.36	4.03	3.84	4.65	8.49	2.55	7.84	10.39	3.82	7.60	11.41	2.92	5.70
25	2.26	1.88	4.14	1.18	3.92	5.10	2.32	1.09	3.40	3.38	2.46	5.84	2.12	4.72	6.84	3.50	5.49	9.00	2.46	3.26
26	2.38	1.20	3.59	1.49	2.75	4.25	2.74	1.14	3.87	2.85	2.60	5.45	2.35	3.53	5.88	3.43	2.77	6.21	2.54	2.33
27	4.60	11.72	16.32	1.46	1.50	2.95	2.84	0.59	3.43	3.44	1.97	5.41	1.99	2.68	4.67	2.80	2.91	5.71	2.85	3.56
28	2.61	7.28	9.89	1.70	0.58	2.29	2.19	1.24	3.43	2.26	0.89	3.15	1.45	1.20	2.65	2.68	0.55	3.23	2.15	1.96
29	1.98	0.54	2.52	2.10	2.75	4.85	3.45	2.83	6.28	3.42	4.82	8.24	1.84	1.67	3.51	3.08	2.47	5.55	2.64	2.51
30	3.16	3.44	6.60	2.45	3.14	5.60	2.15	2.90	5.05	2.82	1.70	4.52	1.61	1.19	2.80	3.16	0.79	3.95	2.56	2.19
31	2.80	1.97	4.77	3.47	3.45	6.92	2.34	1.70	4.03	1.94	0.08	2.02	1.52	1.73	3.25	3.55	3.73	7.29	2.60	2.11
32	2.52	2.25	4.76	2.23	1.38	3.61	1.25	1.14	2.39	3.33	4.94	8.27	2.28	2.47	4.75	2.70	2.47	5.17	2.38	2.44
33	2.54	2.26	4.79	1.35	3.14	4.49	1.98	0.86	2.84	2.53	1.59	4.12	1.77	1.34	3.11	3.30	2.25	5.55	2.25	1.90
34	3.18	3.36	6.54	1.31	1.60	2.90	2.32	0.69	3.00	2.61	1.97	4.58	1.13	1.60	2.73	2.85	3.48	6.33	2.23	2.11
35	2.10	0.71	2.80	1.18	1.35	2.53	1.76	0.17	1.92	2.25	1.61	3.86	1.35	2.40	3.75	2.94	2.27	5.21	1.93	1.42
36	2.95	0.44	3.39	2.02	1.86	3.88	3.19	0.56	3.75	3.97	0.63	4.60	2.79	1.43	4.22	3.49	1.07	4.56	3.07	1.00
37	4.71	1.28	5.99	3.65	4.03	7.67	6.97	2.64	9.61	5.32	3.38	8.70	4.56	0.56	5.12	2.47	1.66	4.13	4.61	2.26
Total	50.64	62.51	113.15	32.46	75.97	108.44	46.56	37.87	84.43	51.67	59.73	111.40	35.33	49.19	84.52	53.10	55.10	108.20		

Table S4. Reach-wise silt volume computed from the bar area of the Kosi River (in last 54 years).

Reach	1972 (10^6 m^3)	1980 (10^6 m^3)	1992 (10^6 m^3)	2000 (10^6 m^3)	2009 (10^6 m^3)	2016 (10^6 m^3)	Average (10^6 m^3)	Zone
1	49	39	30	18	16	18	28	III
2	68	57	38	24	32	32	42	IV
3	58	49	26	27	27	30	37	I
4	54	41	14	26	35	37	35	III
5	67	59	16	26	32	39	40	III
6	40	34	25	32	35	41	35	III
7	39	33	23	33	34	47	35	III
8	38	26	29	32	26	30	29	III
9	33	50	57	63	64	63	55	V
10	53	68	66	72	68	64	65	V
11	56	63	71	59	58	51	60	V
12	54	63	54	57	52	53	55	IV
13	52	62	59	57	58	58	57	IV
14	67	76	54	73	69	70	68	V
15	78	80	59	74	63	63	70	V
16	91	77	47	65	65	70	70	V
17	54	62	37	39	55	51	50	IV
18	47	62	31	46	46	40	45	V
19	68	59	20	52	44	59	50	IV
20	38	45	43	50	42	29	41	IV

21	16	48	30	36	18	17	27	IV
22	13	40	36	37	10	21	26	III
23	28	39	5	19	22	13	21	III
24	11	17	3	10	17	16	12	III
25	4	8	2	5	10	12	7	II
26	3	6	2	6	8	6	5	I
27	25	3	1	4	6	6	8	II
28	16	1	3	2	3	1	4	I
29	1	6	6	10	4	5	5	I
30	7	7	6	4	3	2	5	I
31	4	7	4	0.17	4	8	5	I
32	5	3	2	11	5	5	5	I
33	5	7	2	3	3	5	4	I
34	7	3	1	4	3	7	5	I
35	2	3	0.37	3	5	5	3	I
36	1	4	1	1	3	2	2	I
37	3	9	6	7	1	4	5	I
Chatara –Birpur (1-8)	412	338	191	221	237	274	279	
Birpur–Baltara (9-37)	842	976	709	871	809	803	835	
Total (in last 54 years)	1254	1314	900	1092	1046	1077	1114	
Annual silt volume (approx.) Chatara–Birpur (1-8): 5.16 x 10^6 m^3 Birpur–Baltara (9-37): 15.46 x 10^6 m^3								

Note: The shaded rows are the major hotspots of aggradation falling in zones IV and V.

References

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