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Fluvial System Responses to Land Use Land Cover Change: A Study on Lower Section of Barakar River Basin, India

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Abstract: *The changes in land use and land cover in the river basin drives long-term modifications in the river hydrology, sedimentology and morphology. The Barakar river is the principal tributary of the Damodar. The major changes of the land use land cover of the river basin include increase in the build-up area and agricultural land and reduction of the vegetation cover. The hydrological impact of such changes in land use land cover is manifested in the increase of minimum discharge and the fluctuation of the wet season discharge are the result of the land use changes over the studied period from 1992 to 2011. The reduction of vegetation cover increases the surface flow during the rainy season that leads to fluctuation in the wet season discharge. The reduction of the vegetation cover and increase of barren lands leads to the soil erosion in the catchment area and reservoir sedimentation started increasing from the last decade of the late 20th century. The land use changes also modify the river morphology, such as changes in planform, sinuosity ratio and braid-channel ratio. The related changes in bed form include width, length and area of the mid-channel bars, point bars etc. The rainfall, tectonic activity and human activities play a role in the modification of sediment supply and thus affect the aggradational and degradational processes of the river. The current pace of changes can lead to further modification in future which can be a cause for concern regarding the fluvial health of Barakar river system.*

Introduction

In the twentieth and twenty first century, encroachments on natural resources in the environment are predominant. Human encroachments on the water resources are increasing rapidly. Human activities affect the river channel and morphology in many-ways — through engineering works, industrialisation, and urbanisation and through changes in land use and land cover (Gregory, 2006). Two most prominent forms of land use changes in a river basin are forest clearance and urbanisation (Knighton, 1998). The changes in land use and land cover in the river basin drives long term modifications in the water resources, river hydrology and morphology (Calder, 2000). Several studies reveal that deforestation causes an increase in the mean annual discharge, which in its turn affects the channel morphology in the downstream reaches. Land use land cover (LULC) change has its impact on flow regime, runoff generation and different components of basin and sub-basin hydrology (Kashaigili, 2008; Niehoff *et al*., 2002; Thanapakpawin *et al*., 2006; Salemi *et al*., 2013; Costa *et al*., 2003; Nei *et al*., 2011; Öztürk *et al*., 2013). Forest clearing and subsequent change in grazing affects the water yields of the river (Genwei, 1999; Siriwardena *et al*., 2006). Land use changes and management practices can improve the surface and groundwater quality in the riparian floodplain area of the river systems (Krause *et al*., 2008). Land use changes, especially reduction in forest cover modify the surface runoff and sediment delivery, sediment yield and enhance soil erosion (Bi *et al*., 2009; Verstraeten and Prosser, 2008; Zhang *et al*., 2010; Gebremicael *et al*., 2013; Ward *et al*., 2009; Kondolf *et al*., 2002; Walling, 1999; Rompaey *et al*., 2002; Moor *et al*., 2008). On the contrary, reforestation and afforestation programme decrease rainfall erosivity, which reduces the sediment supply of the watershed (Boix-Fayos *et al*., 2007). Not only the hydrologic variation, but also geomorphic and ecological characteristics of the river health has been affected due to land use changes (Poff *et al*., 2006). Modifications of the vegetation cover and gravel mining either widen or narrow down the channel and also modify the channel depth by incision or aggradation (Comiti *et al*., 2011). Dominance of grazing and removal of vegetation in the basin reduce moisture storage and increase the rate of runoff (Harden, 2006).

Increase in built up land and urbanisation are one of the major causes for changes in channel pattern and geometry(Gregory and Walling, 1973) viz. increasing the channel cross-sectional area, sediments and runoff of the streams (Kang and Marston, 2006). On a global scale, over 83% of the land surface has been significantly influenced by the human footprint on ‘wild lands’ and this percentage is even higher in the continental US (Sanderson *et al*., 2002). Major quantification and evaluation of the effect of human induced land use changes are on hydrology, sediment flux and channel geometry of the fluvial system (Kale, 2002; 2009). However, it is still unknown that what magnitude of interventions could be harmful for the health of the river.

The present study seeks to focus on temporal (1992–2011) changes of land use/ land cover of Barakar river basin and its impacts on hydrology, sedimentology and morphology especially one dimensional (width and depth of the river channels) and two dimensional changes (planform, thread, channel geometry changes) of the Barakar river system.

Previous works

Impact of land use land cover changes of the river basin on river health is significant. Several studies across the world reveal the significant impacts. Roksandic *et al*., (2011) have assessed bank erosion, using the positional shift of the river in two time periods, divided by the total length of the river course in the previous year, as a factor of soil loss and land use changes in the Kolubara River basin of Serbia. In the area, they have found that bank erosion, silt accumulation and floods are major environmental problems that are caused by land use changes. Using a different model, Nei *et al*. (2011) have evaluated the impacts of land use land cover (LULC) changes on the hydrology of upper San Pedro watershed with the help of Soil and Water Assessment Tool (SWAT). This model works on the digital elevation model (DEM), LULC maps, climatic and soil character of the drainage basin and correlates these with evapotranspiration, surface runoff, percolation, sub-surface flow, groundwater flow and transmission losses through multiple regression analysis. Thanapakpawin *et al*. (2006) have evaluated the impact of land use change on hydrology by using Distributed Hydrology Soil Vegetation Model (DHSVM) model to show how land use and climate change affects runoff generation. He considered parameters like topography, flow network, soil attribute, vegetation and land use in this model. Verstraeten and Prosser (2008) have modelled the impacts of land use changes on hill slope sediment delivery to the rivers with the help of Soil Erosion and Sediment Delivery Model (SEDEM) and Revised Universal Soil Loss Equation (RUSLE). Genwei (1999) has assessed the hydrological effects due to forest clearance in the upper Yangtze valley with the help of the runoff coefficient and the conservation index to establish the fact that forest clearance leads to increase in soil loss and reduction of annual runoff and flow rate. Kondolf *et al*. (2002) have investigated the increase and decrease of bed load supply in river channel due to land use changes through aerial photographs, hydrological data and field observations. Preciso *et al*. (2011) have assessed the changes in channel morphology and sediment flux due to changes in land use and other factors, based on several time series aerial photographs and field surveys in the Reno river of Italy. They have observed the increase of suspended sediment in cropped and pasture lands rather than in the dense forest area. The analysis reveals that land use land cover changes on the catchment have impacts on river sedimentation, hydrology that further modify the morphology.

Regional settings

The Barakar river is the main tributary of the Damodar river in eastern India. Originating near Padma in Hazaribagh district of Jharkhand it flows for 225 km across the northern part of the Chotanagpur Plateau (Singh, 1971), mostly in a west to east direction, before joining the Damodar near Dishergarh in the Bardhhaman district of West Bengal (Fig. 1). It has a catchment area of 6,987 km2 and the main tributaries Barsoti and Usri join the Barakar from the south and north respectively. The studied section consists of the Hazaribagh plateau, the dissected uplands of plateau fringe and the aggradational plain of Jharkhand and West Bengal (DVC, 1995). In the upstream region, the Barakar river flows over rugged topography in the gneissic areas (Sen and Prasad, 2002) with prominent narrow incised valley. In the upstream reach of the Maithon and Tilaiya Dam, aggradation process predominates, with relatively wide valley. In the downstream reach the water flow is regulated by the dam, where the river flows over degraded bedrock surfaces. At the confluence point, where sandstones are exposed as bed rock several potholes have formed with maximum diameter of 2 meters, indicating high energy condition at this point.

In the plateau fringe and adjoining plain area soil erosion is prominent with rates above 3.5 t $ha^{-1}yr^{-1}$ (Pandey *et al*., 2007). Land use change from forested to agricultural land is also prominent. The main types of soil that are present in the area are alfisol and inceptisol

(Ezaruddin, 2004). The elevation of this area varies from 150 to 400 m and the average annual rainfall of the region ranges from 1300–1400 mm yr^{-1} (Subash *et al.*, 2011). This region is rich in minerals and mining activities are predominant in the region. In the river, sand mining occurs in the downstream areas, especially in the downstream area of Maithon dam. The downstream stretch of the Barakar, after the confluence of Usri river, is considered for the present study.

collected from the sources mentioned in Table 1. The basin delineation is done using the topographical sheets (1:50,000) and ASTER DEM. From the satellite images, the basin area has been extracted and it has been classified into six land use categories with supervised classification (Joshi and Nagare, 2009) viz. built up areas, barren land, agricultural land, reservoirs, river and vegetation. The land use categories have been identified and the category wise change in

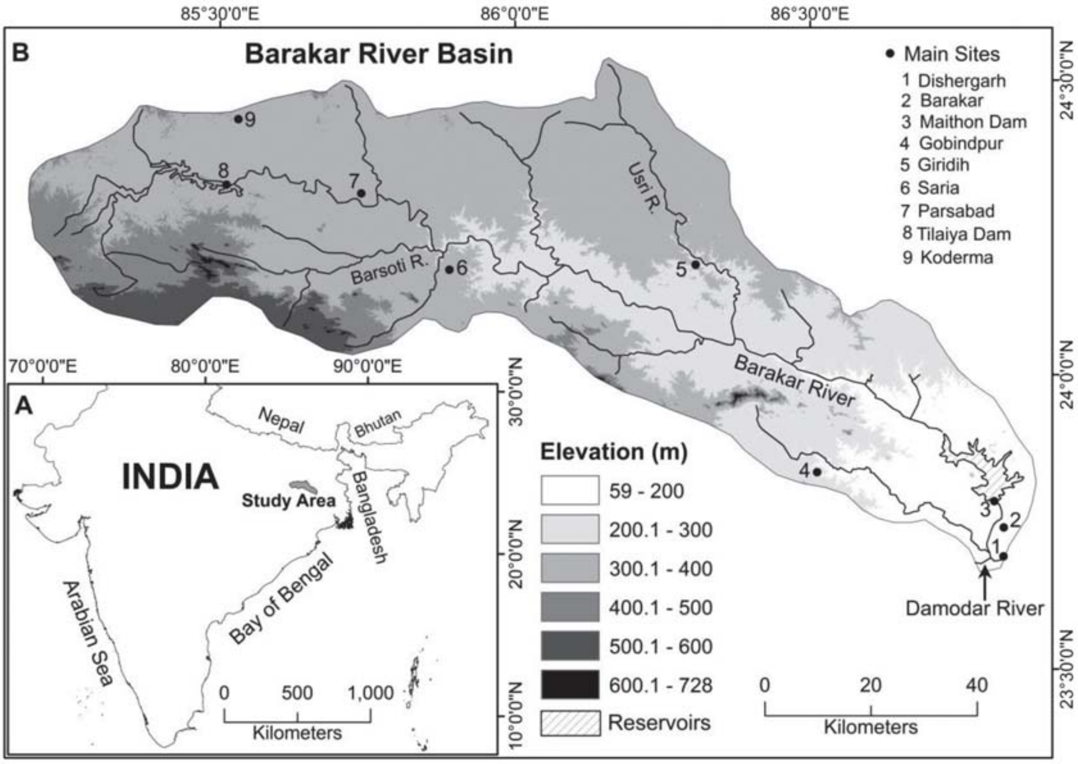

Figure 1. (A) Location map of the Barakar river basin. (B) Physiography and major rivers of the Barakar River basin based on ASTER DEM (2011).

Materials and methods

The secondary and primary data used for the present work has been summarised in Table 1 and 2 respectively.

To evaluate the effect of land use land cover changes on the river system satellite imagery of different time periods has been land use at different time periods has been calculated. The land use categories have been authenticated with the ground truth verification during the field survey. The change of land use land cover in two temporal contexts is given in tabular form in Table 3 and 4.

Table 1. Secondary data sources used for the study

Data types	Data Sources
River discharge data	Hydraulic data Division, DVC, Maithon, DVC Headquarters, Kolkata (1950-2010)
Sediment data	Hydraulic Data Division, DVC, Maithon
Rainfall data	Indian Meteorological Department, (1950-2010); Hydraulic Data Division, DVC, Maithon, (1994-2006)
Satellite images	USGS Earth Explorer- Landsat 5 (1992, 2010);
Digital elevation data	USGS Earth Explorer-SRTM (2005), ASTER DEM (2011);
Topographical map	Survey of India (72H/7, 72H/8, 72H/11, 72H/12, 72H/15, 72H/16, 72L/4, 72L/8, 73I/9, 73I/13, 73I/14) (1:50000)
District Planning Map series	National Atlas and Thematic Mapping Organization (NATMO).

Table 2. On-field data generated for the study

Location of site	Channel width and depth (m)	Land use land cover practices including human influences	Dominant channel bed characteristics	Geomorphic features
23°44′28″ N	258.8	Left bank: build up land, barren grassland	Left bank: sand, coarse sand	Rills and gullies, sand ripple, terraces
86°48′29″ E	13.4	Right bank: bared rocky land, build up land.	Right bank: bedrock	
		Rail and road bridge, embankment (80 m), sewage water mix.		
23°41′38″ N	542.83	Left bank: barren grass and rocky land	Left bank: sand, coarse sand	Pothole, avg. diameter is 0.92 m
86°48′12″ E	8.65	Right bank: agricultural land. Sand mining, bamboo bridge, coal mining, cremation	Right bank: bedrock (sandstone)	confluence point, stable rocky confluence bar
23°55′25″ N 86°39′25″ E	266.4 10.39	Both banks: barren land, shrub, grassland. road bridge, sand mining	Rocky structure, including bank sand deposition	Point bars, terraces, potholes
24°13′16″ N	190	Both banks: barren land, shrub, agriculture, settlement.	Sandy, bedrock controlled with sand deposits	Unstable mid channel bar, terraces
85°54′04″ E	6.996	Road bridge, vegetation removal		

To measure the channel depth, width and topographic variability in the studied stretch of Barakar river valley, several cross sections have been marked with the help of ASTER DEM and it was authenticated with field measurements. The width-depth ratio of the channel varies from the aggradational flat plain to the degraded and dissected uplands of the plateau region. The hydrological impact of land use change have been analysed over the given time period with the daily water discharge data available during 1985–2013 from the Damodar Valley Corporation (DVC) Hydrological division of Maithon station. Long term hydrological discussion is not possible because of the unavailability of daily water discharge data. The annual water discharge data are available from the post dam period. The maximum, minimum and annual discharge have been analysed by the Q_{max}/Q_{min} ratio to show peak discharge, lowest discharge and discharge variability at Maithon over the period under study respectively (Latrubesse *et al*., 2005). Discharge variability in wet and dry season has been analysed to show the seasonal fluctuation in discharge and rainfall. The wet season has been considered from June to October and the dry season from November to March, when there is hardly any rainfall except the western disturbances. Due to unavailability of sediment yield data of the Barakar river at Maithon, the trend of sedimentation has been analysed with the sediment deposition rate in Maithon reservoir from 1955 to 2002 to put some light on the sedimentation rate in the river system (Hardon, 1993).

The impacts on the morphology of the river are also a reflection of the changes in land use and land cover in the past decades. The width-depth ratio has been calculated from field survey with the help of the Laser Distance Meter, and SRTM DEM of the studied section. One dimensional change, viz. the width-depth ratio (Wallick *et al*., 2007) has been calculated in the upstream and downstream reaches of the Maithon Dam to show the changes in the operating process and its influence on the channel bed. The two dimensional changes (Wallick *et al*., 2007) of channel bed geometry and planform change is evaluated on the basis of satellite images (1992–2011) in several stretches where the significant changes have been observed (Harmar and Clifford, 2006, Bandyopadhyay *et al*., 2013). The temporal changes in channel width, length and configuration of within-channel bars have been estimated from satellite images and topographical maps (Kiss and Blanka, 2012). To assess the channel bed characteristics over the given time period, the Sinuosity Index and the Braid-channel Ratio of the different reaches have been analysed from 1992–2011, which has helped in dividing the studied reach into 10 divisions of 5 km each. This helps to depict the aggradation and degradation processes and the dynamicity of the river channel. Braid-channel Ratio is considered instead of the Braiding Index as the latter has considered the sinuosity parameter also (Friend and Sinha, 1993). Decadal monthly precipitation change can also be established with the help of rainfall data at an interval of 10 years to show the effect of land cover changes on precipitation.

Result and analysis

Land use land cover changes in the Barakar basin

The land use land cover changes of the Barakar river basin in 1992 and 2011 have been shown in Figure 2. The major changes of LULC are depicted in Table 3 and 4. In 1992, agricultural land and vegetated land occupied a significant place in the land use of

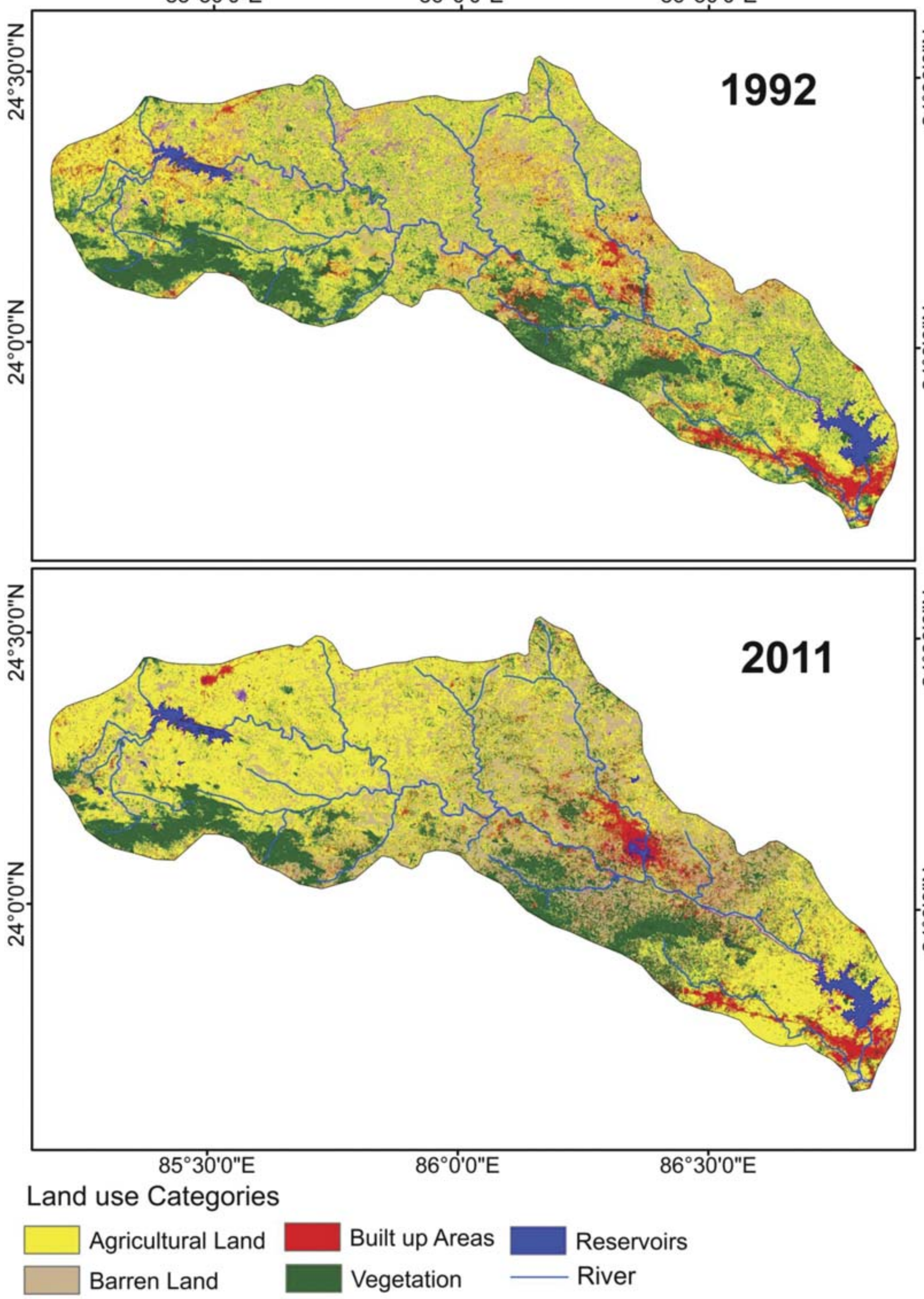

Figure 2. Land use land cover changes of the Barakar River basin (1992-2011)

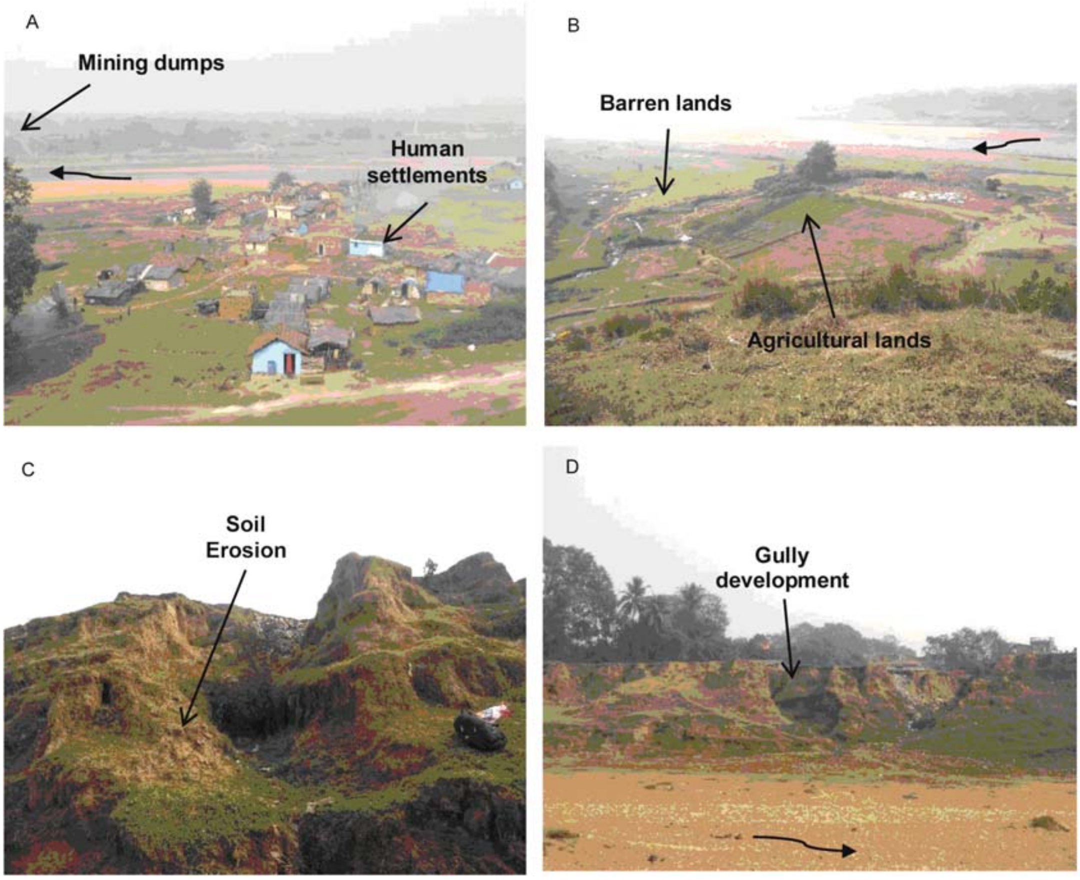

Plate 1. Land use practices at the Barakar River and its surroundings and impacts on the river regimes. A. The human encroachments on the river through the settlements and mining dumping at the bank side, B. Barren lands and Agricultural lands at the river bank. C. Soil erosion at the river bank due to the removal of riparian vegetation. D. Rills and gully development at the left bank of the river as the result of land use changes along the river bank. Arrow mark represents channel flow direction.

Table 3. Land use land cover changes of the Barakar River Basin (1992-2011)

Land use categories	1992		2011	
	Area (ha.) %		Area (ha.) %	
Agricultural land	300070.2	42.904	312225.3	43.99
Barren land	158368.4	22.643	192808.1	27.165
Build up areas	39523.84	5.651	53003.97	7.467
Reservoirs	10282.19	1.47	14830.83	2.089
River	10809.2	1.545	9704.61	1.367
Sand	2567.14	0.367	2087.52	0.294
Vegetation	177767.3	25.417	125096.5	17.625

this region covering 42 and 25 per cent of the total area respectively. The barren lands also show significant occupancy in the land use (22% of total land). Most of the basin is in the plateau fringe area that is why the barren land occupies a significant place. The rest of the land use categories are insignificant in 1992. The reservoirs and the rivers occupied less than 2 per cent of the total land use. In this region two prominent reservoirs are Tilaiya and Maithon on the Barakar River.

In 2011, agricultural land and vegetated land still occupied dominant positions in the land use of this region with 43 and 17 per cent respectively (Table 3). There is drastically increasing barren land (22–27% of total land use) from 1992 to 2011. Increase in the agricultural land from 42 per cent in 1992 to 43 per cent in 2011 is the result of the increase in population and deforestation. Reduction of vegetation (25% to 17% of total land use) is the major cause for the increase in barren land in this river basin. Increase of agricultural land is also one of the causes for the reduction vegetation cover. Increase in the percentage of built-up area (5% to 7%) has also intensified the reduction of vegetation cover. Significant changes have not been observed in the rest of the land use categories though slight increase in reservoir area and minor decrease in the area under river and sand can be observed.

The annual rate of land use change is not very significant (Table 4). The vegetation cover has highest rate of reduction with 0.41% yr^{-1} and overall 7.79% yr^{-1} in the period from 1992–2011. The barren land has also shown significant positive changes in this period with an overall, rate of 4.52% yr^{-1} and 0.24% yr^{-1}. Among all the land use categories, vegetation cover has the highest amount of negative change. The negative change in areas under river and sand is not very significant. The built-up area has increased at a faster rate than agricultural land with an overall change of 1.82 per cent and 0.95% yr^{-1}. The annual positive change of 0.032% yr^{-1} for reservoirs is not significant in this given time period.

Land use land cover change in the river basin is one of the external variables that affect the fluvial system. Major impacts of LULC change are on the hydrology, sedimentation, and geomorphology of the fluvial system (Salemi *et al.*, 2013; Kondolf *et al.*, 2002; Kang and Marston, 2006). The probable impacts of LULC change on the

Table 4. Annual rate of changes of land use land cover (1992-2011)

Land use categories	Change detection of LULC between 1992-2011		
	Area (ha.)	Area (%)	Annual rate of change (%)
Agricultural land	12155.13	1.085	0.057
Barren land	34439.72	4.521	0.237
Build up areas	13480.13	1.816	0.095
Reservoirs	4548.638	0.619	0.032
River	-1104.59	-0.178	-0.009
Sand	-479.623	-0.072	-0.003
Vegetation	-52670.8	-7.792	-0.41

fluvial system have been tabulated as compiled from a number of previously published (Table 5).

Impacts on hydrology and sedimentation

An increasing trend of annual minimum discharge (Q_{min}) in monsoon period has been noticed (Fig. 3B) over the given time period. This indicates increase in water availability in the dry period. Post 1998, increase of annual minimum discharge (Q_{min}) may be attributed to reduction in infiltration rate and increase in runoff through the conversion of vegetation cover to other land use categories (Kashaigili, 2008). No significant trend is observed in the annual maximum discharge i.e. Q_{max} (Fig. 3A) and in the Q_{max} and Q_{min} ratio (Fig. 3C). This indicates the reduction of the flood peaks in the Barakar river. The discharge of the river has been mainly controlled by the monsoon rainfall. The temporal discharge variation has been analysed in two seasons — wet (June to October) and dry season (November to March). From the Fig. 3D, it can be observed that the discharge do not show much variation in the dry season, while in the wet season the discharge is significantly fluctuating and it ranges from 140 $m3s^{-1}$ (2007) to 2700 $m3s^{-1}$ (2010). In the period 1992–1999, the trend of discharge is continuously increasing, but from 2000–2004, it remains almost constant. The fluctuation of discharge is most significant after 2004 to present. Such variability in discharge may be because of land use changes. Urbanisation has rapidly gained pace in the 21st century and the vegetation cover has decreased about 7.7% over the studied period (Table 3). The land use land cover changes lead to slight reduction in minimum discharge (Q_{min}), but hardly significant changes in the maximum discharge (Q_{max}). The discharge variability at Maithon might be due to modification of discharge from the Tilaiya dam near the source of the Barakar river.

Table 5. Probable influences of land use land cover on the river system

Land use land and cover	Changes	Impacts on hydrology of the river	Impacts on sedimentology of the river	Impacts on morphology of the river
Vegetation	Negative	Increase of water discharge	Increase of suspended sediment load	Changes in the braid-channel ratio, increase of bank erosion
Barren land	Positive	Increase of water discharge	Increase of suspended sediment load	Changes in the braid-channel ratio, Increase of bank erosion
Build up areas	Positive	Increase of water flow through channelised flow	Constant or decrease in suspended sediment load	Reduction in width through embankment construction
Agricultural land	Positive	Changes in water quality	Increase of suspended sediment load	--

Rate of sediment deposition declined in the initial phase of the Maithon dam construction in 1957 (Fig. 4). In between 1963–79, sediment deposition is less than the mean of the whole time period. After 1980, an increasing trend of deposition can be

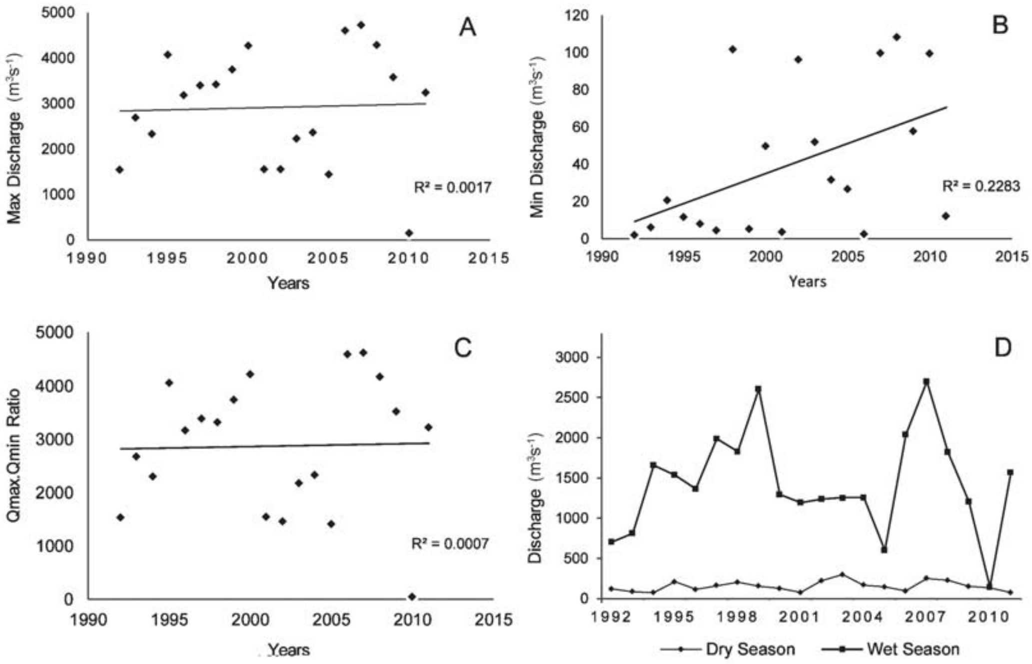

Figure 3. Hydrological analysis over the studied time span (1992-2011) in the Maithon gauging station on the Barakar river. A. Maximum discharge (Q_{max}), B. Minimum discharge (Q_{min}), C. Q_{max}. Q_{min} ratio, D. Discharge variability in the wet and dry season.

observed. An increase in the suspended and bed load sediment of the channel accelerates the sedimentation. The increase of sedimentation trend may be caused by reduction in vegetation cover in the river basin that leads to soil erosion and land degradation in the catchment areas and increase in suspended and bed load of the river as well as in the reservoir (Ward *et al*., 2009). Consequently, braided condition of the river bed has become more pronounced since 2011. But it can also be mentioned that land use change is not solely responsible for the increase in sediment yield and sedimentation of the reservoirs. Climatic phenomena also play a major role.

One dimensional morphological change

One dimensional morphological change includes width-depth characteristics of the river system (Wallick *et al*., 2007). Several cross sections along the studied reach reveal the variability in the width of the channel, which is in almost all sections more than the depth. Except the cross section downstream of the Maithon dam, all the cross sections are more or less constant in depth. The effects of dam on the width, depth and width-depth ratio are also significant. From Gulaidi (upstream) to Panjania (downstream), width-depth ratio is constantly increasing from 28 to 52. But, drastic reductions of width-depth ratio are observed from 100 to 20 from Maithon to the confluence point with the Damodar at Dishergarh (Fig. 5). Dam construction is solely responsible for such type of reduction in the width-depth ratio. The Maithon dam acts as a local base level that increases the capability of erosion in the downstream section of the dam. Removal of the vegetation

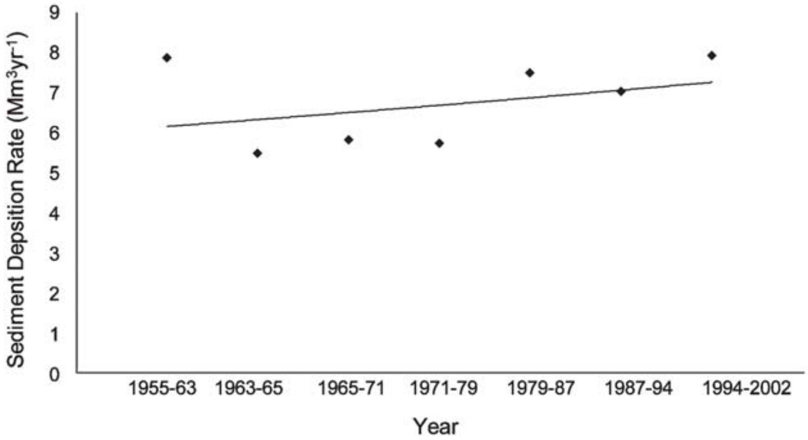

Figure 4. The trend of sediment deposition rate of the Maithon reservoir (1955-2002).

cover for cultivation, engineering constructions and built up areas enhanced the soil erosion and sediment yield that accelerated the silting and aggradation processes in the downstream areas, altering the width-depth ratio in the process.

braided, anastomosing and single or multiple thread channels (Wallick *et al*., 2007). The planform of the channel has been modified by the land use changes in the lower section of the Barakar river. Two different sections: upstream (Fig. 6A and B) and downstream

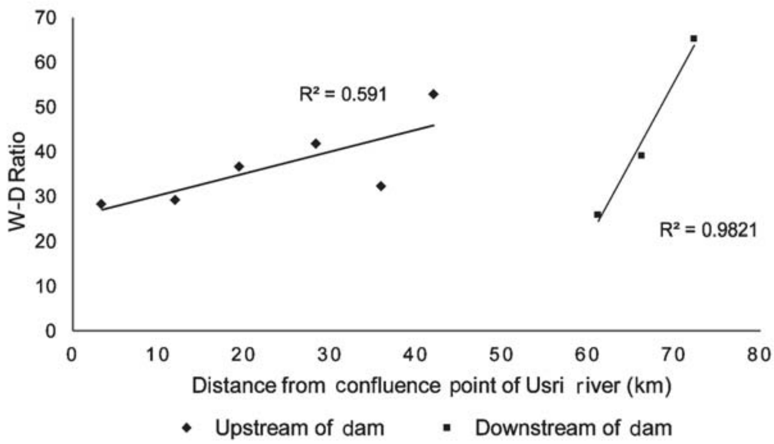

Figure 5. W-D Ratio along the channel of the lower Barakar River. The W-D ratio is increased in upstream as well as downstream of the Maithon Dam, but is high in downstream of the dam where rapid land use change is discernible.

Two dimensional morphological changes

CHANGES IN PLANFORM GEOMETRY: Two dimensional changes include the planform adjustment with the focus on meandering, (Fig. 6C and D) of Maithon Dam has been analysed in 1992 and 2011. Four stretches have been selected along the river to analyse planform geometry of the surveyed portion.

The major changes include the changes of the bars from 1992 to 2011. In stretch A, the size of the point bars in 1992 was 820 m but it is reduced to 650 m in the year 2011, with overall, 170 m (21%) reduction in length of the bar. Stretch B, immediately upstream of the Maithon dam, represents the reduction in the number of sand deposition or bars, but the length of the point bars has increased in 2011 in comparison with 1992. Increase of area (52%) of point bar from 0.53 km^2 to 0.81 km^2 is significant. The changes in shape (lobate to elongated) of point bar is also a prominent feature in stretch B, where flow is more or less constant being in the upstream of the Maithon reservoir (Joshi and Gaikhe, 2009). Here, the trend of reduction in size of bars and sand deposition may be attributed to the increasing trend of annual minimum discharge (Q_{min}) as recorded at the Maithon gauging station.

Figures 6C and 6D shows the planform of the downstream section of Maithon dam, in the lower reach of the Barakar river. Stretch C is in the upstream and stretch D is downstream of Barakar town respectively. In stretch C, a point bar in the right bank of the river was prominent in 1992 but, in 2011 the main flow path of the river shifted, and obliterated the point bar. On the other hand, left bank planform has not changed significantly. Stretch D is located upstream of the confluence point with the Damodar. In this stretch planform geometry has not changed significantly. The sizes of the point bars have decreased from 1992 to 2011. In 1992, length of the point bar was 1085 m, which reduced to 745 m in 2011. There is about 340 m (32%) decrease in the length of the point bar on the left bank. On the contrary, sand deposition on the right bank has increased during the above

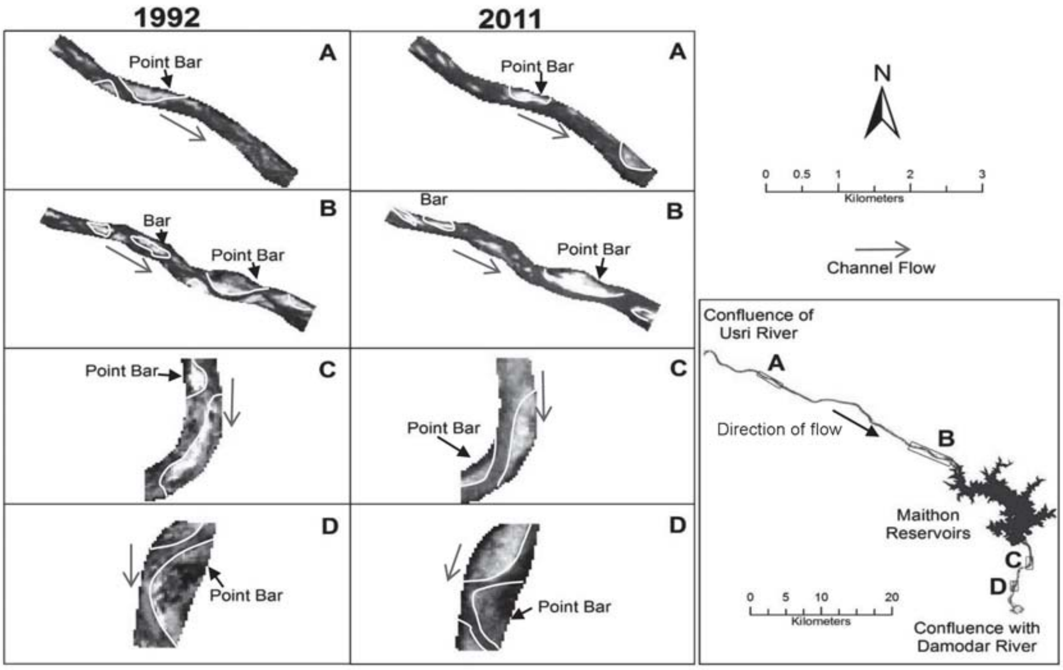

Figure 6. Planform dynamics of the lower Barakar river. Planform has been analysed using four . The windows A, B, C, D indicate the planform that has changed significantly over the studied period (1992-2011).

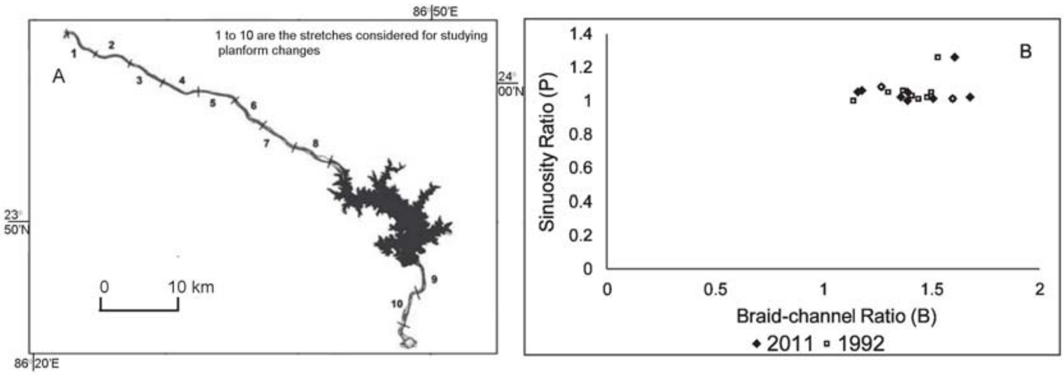

Figure 7. A. Diagrammatic map of the studied section that has been divided into 5 km reaches to calculate the Sinuosity Index (P) and Braid-channel ratio (B). B. Temporal changes of Sinuosity Index (P) and Braid-channel Ratio (B) in the lower section of the Barakar River (1992-2011)

mentioned time period. Controlled release of water may be one of the causes for reshaping the planform geometry. Increasing area under built up area may also be the reason for the increase of flow and reshaping of bars and sand deposits.

CHANGES IN THE BRAIDING AND SINUOSITY PARAMETERS: The braiding and sinuosity indices quantify the channel geometry whether it is a, single thread or multi thread channel. The entire reach under study has been divided into ten sections (Fig. 7) of 5 km each. The sinuosity index and the braid-

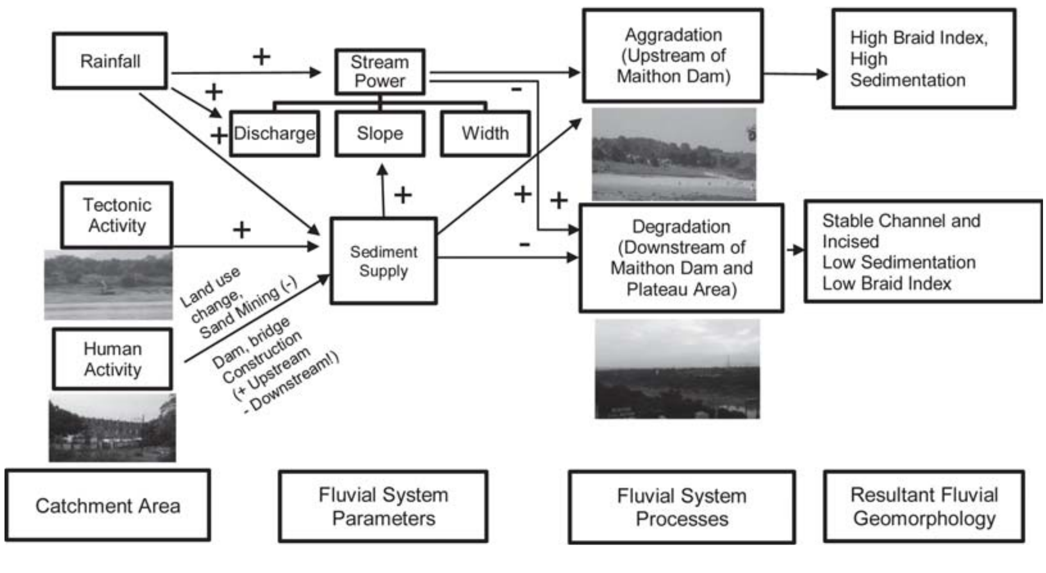

Figure 8. Process response system depicting the relationship between catchment and fluvial parameters, fluvial processes and the resultant geomorphology of the Barakar river system. Positive (+) and negative (-) signs indicate the feedback (Based on Sinha *et al.*, 2015)

channel ratio have been calculated for the analysis of channel geometry.

The Sinuosity Index (P) has been calculated based on the following equation:

$$P = L_{emax} / L_R$$

where, L_R is the length of the channel-belt measured along a straight line, L_{emax} is the mid-channel length for the same reach or the mid-channel length of the widest channel (where there is more than one channel).

The Braid-channel Ratio (Friend and Sinha, 1993) has been calculated as:

$$B = L_{etot} / L_{emax}$$

Where, L_{etot} is the sum of the mid-channel length of all the segments of the primary channels in a reach, and L emax is the mid-channel length of the widest channel in the studied reach.

Figure 7 shows the temporal change in Sinuosity Index (P) and the Braid-channel ratio (B) along the studied section of the Barakar river. The sinuosity values are generally low (as the values are lying in around 1), except the 9th section where the value is above 1.26. The channel planform, throughout the studied reach can be categorised as sinuous rather than meandering as the Sinuosity Index is <1 (Prasad, 1982). Temporal change (1992–2011) of Sinuosity Index is not significantly observed. Major portion of the river is bedrock controlled. That is why the river does not exhibit any significant trend of meandering or meander shifting. The Braid-channel Ratio is more fluctuating along the surveyed reach than the Sinuosity Index. The values ranged from 1.27 to 1.60 in 1992. The variation of the Braid-channel Ratio in 2011 is greater than 1992 as the values ranged from 1.16 to 1.68. It is low in comparison with the braided river Gandak (whose value extends up to 5.4) in eastern Gangetic plain (Friend and Sinha, 1993), but the Bagmati river is considered as braided even with a low Braid-channel Ratio of 1.3–1.7 (Sinha *et al*., 2005). So, it can be mentioned that this studied section of the Barakar has slightly braided character. Human encroachment on different sections of the river in 2011 reflects on the multi-channel character of the river than in 1992 (Plate 1). Modification of discharge from the Maithon dam and increase in built up areas may be the reason for the increase of flow and reshaping of sand depositions that contributes to the temporal variation in the Braid-channel Ratio.

Discussion and conclusion

The hydrology and morphology of the Barakar river has been modified as a result of increased human activities in the form of land use land cover change and engineering constructions (Plate 1). The river system has been modified by two major dams of the DVC project and urbanisation is growing in the catchment area. Conversion of the vegetation cover into barren land and to agricultural land from the barren land is significant. Reduction in the vegetal cover leads to accelerated soil erosion in the lower basin, which increase sediment load in the channel. The increasing trend of minimum discharge (Q_{min}) depicts the increase of flow due to removal of vegetation in the dry season, whereas, maximum discharge (Q_{max}) is controlled by the reservoirs. Land degradation and removal of forest lead to increase in suspended and bed load in the river as well as the reservoirs of the dams. Upstream of the dam, channel bar formation is strongly controlled by bed sedimentation; while downstream of the dam the bars are controlled by both structural influence and sediment deposition. It is concluded from the study that rainfall, structural control and human activity influence the fluvial system in terms of stream power and sediment supply that are the key factors for the aggradation and degradation processes of the Barakar river (Fig. 9). Aggradation leads to modification in channel geometry through high sedimentation and high Braid-channel Ratio, whereas, degradation impacts the channel geometry through low sedimentation, low Braid-channel Ratio and incision of the channel. Exposed rocky surface on the bank side and the bedrock channel favoured the fluvial system to maintain its stability. The presence of several potholes on exposed sandstone in the confluence zone of also favoured the stability of the channel at this stretch. But the intensive spread of the urbanisation and reduction of the vegetation cover brings changes in the morphological parameters of the river system. This calls for the necessity of proper watershed management to cope with the pace of changing land use land cover of the drainage basin.

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