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Research Article

IDENTIFICATION OF FLUVIAL AGGRADATION AND DEGRADATION USING REMOTE SENSING AND GIS: A CASE STUDY OF DAMODAR RIVER WEST BENGAL INDIA

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ABSTRACT

In order to locate the sites of progressive erosion and deposition in different segments of Damodar River (Rhondia to Paikpara) the database on bank line shifts leading to degradation and aggradation from 1943 to 2006 (63 years) have been analyzed here with the help of topographical sheets (1943 and 1969-72), IRS LISS III (2001), Landsat MSS (1970, 72 and 73), ETM+ (2000) and TM (2006) images. Hydrogeomorphic processes develop wide fertile floodplain over which the river Damodar continuously alters its course that reshape the valley morphology and develop Quaternary floodplain facies, viz. palaeochannels, levee, terraces, point bars, islands and sloughs etc. The spatial and temporal micro-level changes of Damodar River are analyzed and quantified by the integration of satellite remote sensing, GIS and quantitative geomorphology. The present study reveals that the river in between Rhondia and Barddhaman shows dominance of aggradational landforms, braiding and valley widening but downstream of Barsul up to Paikpara the bank erosion, high sinuosity and narrowness are more pronounced in Damodar River.

Key Words: *Aggradations, Degradation, Sinuosity Index, Braiding Index, Remote Sensing and GIS*

INTRODUCTION

Floodplain is a multifaceted zone where different types of hydrogeomorphic processes act together in a complex manner and this geomorphic unit is remodeled since Late Pleistocene to the Present in respect of climate changes and magnitude of fluvial processes (Bridge, 2003; Sinha and Ghosh, 2012; Mondal and Satpathi, 2012). Bank erosion (degradation) and fluvial deposition (aggradation) are the direct evidence of geomorphic instability phenomenon and it shapes the channel morphology of a particular reach (Garde, 2006; Mondal and Satpathi, 2012). The Palaeoclimatic studies indicate that there were distinct periods of erosion and incision (degradation) and sediment deposition (aggradation) associated with changes in the monsoon conditions and sediment supply. The main fluvial responses to Late Quaternary climate changes in India are: (1) periods of aggradation are linked to periods of weaker monsoon and reduced sediment supply and (2) periods of stronger monsoon are associated with erosion and incision and increased sediment supply to ocean (Rajaguru *et al.*, 1993; Mishra *et al.*, 2003; Singhvi and Kale, 2009). It has been found that satellite remote sensing and Geographic Information System (GIS) offer the better opportunity to gain fresh insights into the fluvial geomorphic system through the spatial, temporal, spectral and radiometric resolution of remote sensing systems and through the analytical and data integration capability of GIS (Walsh *et al.*, 1998; Ghoshal *et al.*, 2010). Using satellite images and GIS the lateral migration, avulsion and bank line shifting of Indian rivers (i.e. Ganga, Brahamaputra, Bhagirathi-Hooghly, Ichhamati, Barak, Pravara, Damodar etc.) are studied by Desai *et al.*, (2010), Roy *et al.*, (2011), Bhattacharyya (2011), Mondal and Satpathi (2012), Sarma and Acharjee (2012), Sinha and Ghosh (2012), Sarkar *et al.*, (2012), Aher *et al.*, (2012), Laskar and Phukon (2012), Das *et al.*, (2012) and Praveen *et al.*, (2012). Having 347 years of miserable flood history, lower Damodar River had been altered its courses below Barddhaman town in Damodar fan-delta since Early Holocene and the severe floods above 18,000 cumec were more common in pre-dam period (pre-1958) (Acharyya and Shah, 2007; Bhattacharyya, 2011). The Damodar River of West Bengal has changed its main course and bank line in several times since 1730 and after dam construction of Damodar Valley corporation (DVC) the bank erosion as well as bar formation is well associated with monsoonal flood flow (Bhattacharyya, 2011; Ghosh and Mistri, 2012a). In order to have spatio-temporal information about present and future trend of erosion and deposition in different segments of lower Damodar River the database on bank line shift leading to degradation and aggradation from 1943 to 2006 have been analyzed here with the help of topographical sheets, satellite images and GIS.

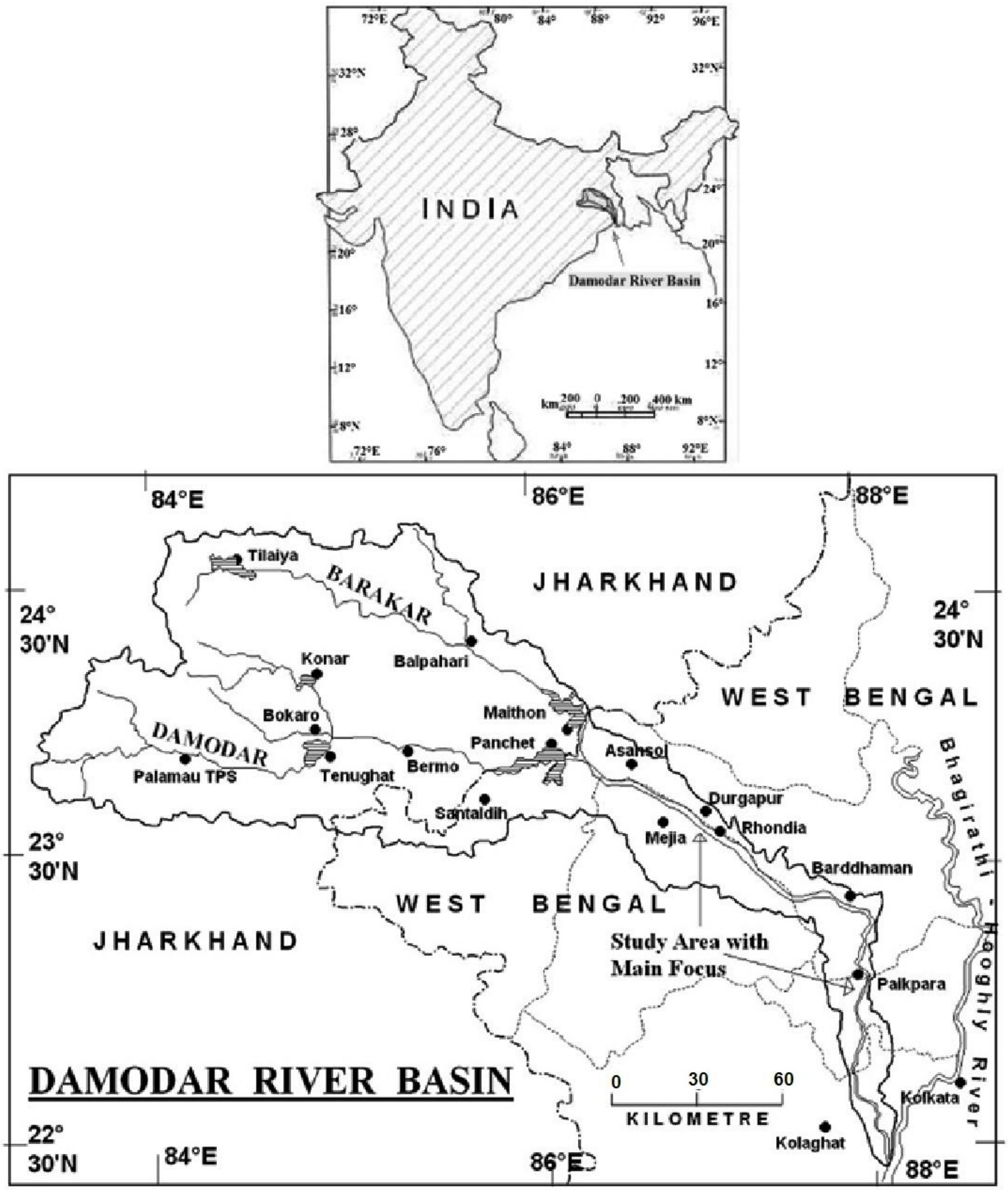

Figure 1: Location map of Damodar River Basin including study area

Study Area

The Damodar River Basin (figure 1) is a sub-basin of the Bhagirathi-Hooghly River system of West Bengal and geologically the floodplain of this region is belonged to the western part of Bengal Basin and geomorphologically it is a mature fan-delta of Damodar River sloping toward east-south east, though its western part is associated with Ajoy – Damodar interfluve 'Rarh Plain' (Sen, 1991; Acharyya and Shah, 2007; Bhattacharyya, 2011; Ghosh and Mistri, 2012a). Its funnel shape basin area is about 23,370.98 km^2, spreading in the states of Jharkhand (73.7 per cent) and West Bengal (26.3 per cent) (Majumder *et al.*, 2010). Damodar River is one of important monsoon dominated and flood-prone Indian Rivers which carries out almost all the geomorphic works of erosion, transportation and deposition during summer monsoon season, mainly June to September (Kale, 2003). For field investigation we have selected the lower reach (23°00´ to 23°22´ N and 87°28´ to 88°01´ E) of Damodar in between Rhondia Andersion Weir below Durgapur Barrage (west) and Paikpara below Jamalpur (east) (figure 1 and 2).

In between Rhondia and Paikpara the total length of Damodar River is approximately 82 km, having numerous glimpses of spill channels and palaeochannels, viz. *Khari*, *Banka*, *Gangur*, *Behula*, *Sapjala*, *Deb Khal* and *Kana Damodar*. There is a sharp physiographic contrast in Damodar River Basin – (1) Upper and Middle Basin is covered by Archean to Gondowana formation, having high relief and (2) Lower Basin below Asansol exhibits newer to older alluvium tract of lower relief (Chandra, 2003). Basically below confluence point of Damodar – Barakar (at Dishergarh, near Asansol City) due to regional tilt and neo-tectonic activity the Damodar River enters into its lower portion of the ancient deltaic basin and after crossing Durgapur the River enters into the Quaternary Old and Recent alluvium plain, filling the Bengal Basin with coarse sediments of Chotangapur Plateau (Dasgupta and Mukherjee, 2006).

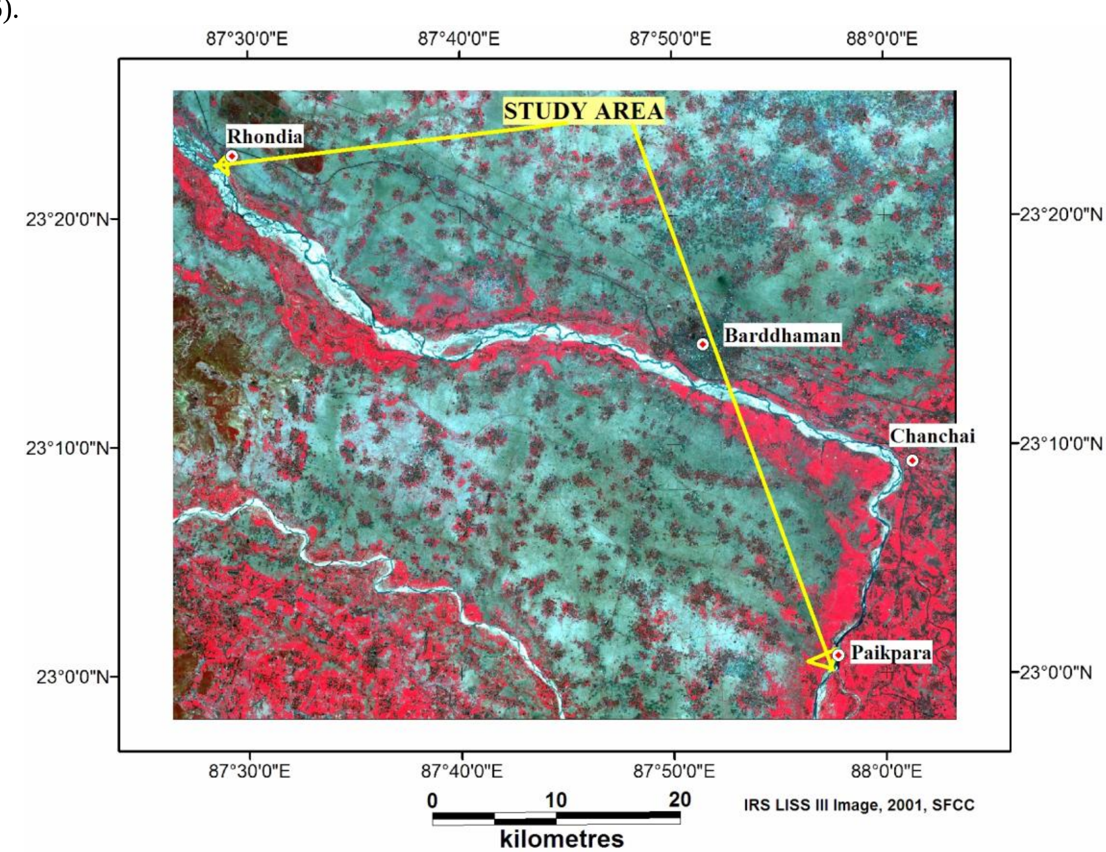

Figure 2: IRS LISS III Standard FCC image (2001) of study area

MATERIALS AND METHODS

Observing the direction of valley, sudden change in plan-form and bed topography we have subdivided Damodar River into three reaches for detail analysis and field work. The three reaches are (figure 2) - (1) Rhondia to Jujuti (Bend I), (2) Belkash to Chanchai (Bend II), and (3) Chanchai to Paikpara (Bend III). The whole analysis has especially incorporated the spatio-temporal variations (pre-dam – up to 1957 and post-dam period – 1958 to 2007) from 1943 to 2006 and for this reason we have used ArcGis 9.2, MapInfo Professional 9.0 and Erdas Imagine 9.1 software taking topographical sheet of NF 45-3 series U502 (1943), SOI (Survey of India) topographical sheets 73 M/7, M/11, M/12, M/15, M/16, N/13 and 79 A/4 (1969-1974), GLCF (Global Land Cover Facility) satellite images of Landsat MSS (1970, 72 and 73), TM (1990 and 2006), ETM+ (2000) and IRS P6 LISS III (2001).

Advance remote sensing data has combined with digital data to extract spatial information and specific up to date simple measurements can perform with this tool (Aher *et al.*, 2012; Sinha and Ghosh 2012). The methodology adopted by Ghosal *et al.*, (2010), Sarkar et al (2012), Mondal and Satpati (2012), Laskar and Phukon (2012), Thakur *et al.*, (2012) and Das *et al.*, (2012), is employed here to fulfill the work. The extracted vector based spatio-temporal information and thematic maps regarding channel migration of Damodar River is indentified. The main emphasis of this work is that the raster and vector database in different layers (same scale and projection) show the actual changes in the river which is called here ‘river or bank shifting’ from the previous course or bank line (topographical sheet and Landsat MSS image) and this change is detected and verified by field works using Garmin Global Positioning System (GPS) receiver and digital camera. Since the topographical sheets procured from Survey of India belong to year 1969-72 (Polyconic Projection and Everest Spheroid, 1956 Datum), there are ample chance of error, if the toposheet data is taken as reference for geo-referencing the satellite images. Therefore, Landsat MSS, TM and ETM+ images have been taken as reference and topographical sheets are converted to the projection system of Universal Transverse Mercator (UTM) and World Geodetic Survey (WGS) 84 datum. Then the geo-referenced raster data of different years are put on each other to compare the changes and the vectors of bank line and main channel are digitized in different thematic layers to get ultimate output and interpretation. Alongside we have used the Mueller’s Standard Sinuosity Index (SSI, 1968), Braiding Index (BI) of Brice (1964), and Braid-Channel Ratio (BR) of Friend and Sinha (1993) to extract few important and new-fangled information in relation to fluvial aggradation and degradation.

RESULTS

Bank Erosion in Pre-dam Period

The flood protection measure has been achieved through the raising of the embankments along riversides, known as ‘jacketing’ from Barddhaman downwards along both Mundeswari up to Baxi near its confluence with Rupnarayan and Amta channels (Sen, 1985 and 1991). In spite of embankments the spilling and breach occur very frequently in the lower Basin. In the post-dam period (up to 1957), there are many vulnerable sites of right bank-side erosion of considerable intensity, because in 1855 approximately 32.19 km of the right embankment from Sungutgolah down to Begua (near Paikpara) was demolished by British Bengal Government to relieve the pressure on left embankment (Bhattacharyya, 2011). To site a few examples, the retreat of valley-side slopes at Jamalpur near the bifurcation point during 66 year (1881-1956) amount to 310 ft (94.488 m metre) and 100 ft (30.48 metre) on the right bank and left banks respectively, indicating an average retreat of 1.34 metre and 0.42 metre per year (Sen, 1991). It has been found that lower course of Damodar from Jamalpur to Duffer Chak shows an increase in width from 320 m to 488 m and decrease in depth from 9.1 to 5.48 metre (Sen, 1991). On overlaying of 1988 and 1956 cross sections (figure 3), the important generalizations of bank erosion are as follows (Sen, 1991).

The shapes of both cross-profiles maintained trapezoidal forms with an almost horizontal or slightly sloping bed of cohesive alluvium,

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Apart from the thalweg, the floodplain is slightly inclined towards east creating large areas vulnerable to floods in consequence of high flood level, and
Valley-side degradation and aggradation of silty and sandy materials of both banks are predominant phenomena in lower Damoder River.

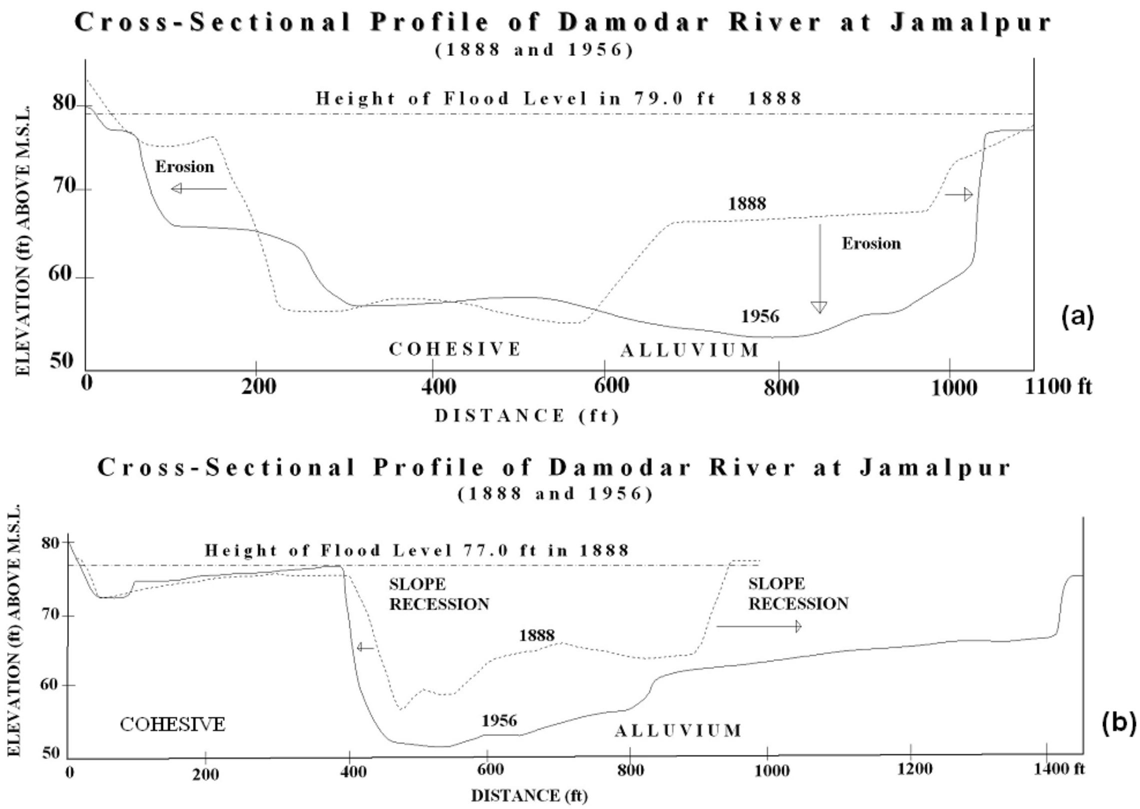

Figure 3: Pre-dam cross-sectional profiles of Damodar River at Jamalpur to show the expanse of bank erosion in between 1888 and 1956 (Source: Sen, 1991)

Shifting Courses of Damodar River

After complete operation of dam construction (1957) by DVC (Damodar Valley Corporation), the processes of erosion and sedimentation have altered radically in response to the regulated stream flow conditions in the lower Damodar and its distributary channels. Comparing the positions of river banks, delineated from topographical sheets (1969-72), Landsat MSS (1972), and Landsat TM (1990 and 2006) images, we have found some vulnerable points causing breaching of embankments and increasing width of active valley. In GIS after systematic overlaying the courses of Damodar of different time we have tried to represent the actual shift of thalweg from pre-dam period to post-dam period using toposheets and satellite images.

At first we have compared and analyzed the positions of active channel path or thalweg in three reaches, viz. Rhondia to Silla, Majher Char to Udaypalli and Udaypalli to Palla Road, using toposheet of 1943 (pre-dam phase), Landsat MSS (1973) and Landsat TM (2006) images (figure 4). From Rhondia Anderson Weir Damodar River is maintained its channel towards far right-side in 1943 than 2006. River now shifts towards to left-side after dam construction, creating alluvial terraces and islands on right-bank side. Though, it is evident from maps that once upon a time the River flowed far left-side that present position, because we have observed the wide stretch of Fathepur Mana (Island) and narrow dry sandy

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river bed. Near Loapur village, in 2006 River thalweg shifts far south in compare to positions of 1943 and 1973. Near Deulpara, in 2006 and 1973 thalweg shifts far north (left side) in compare to position of 1943.

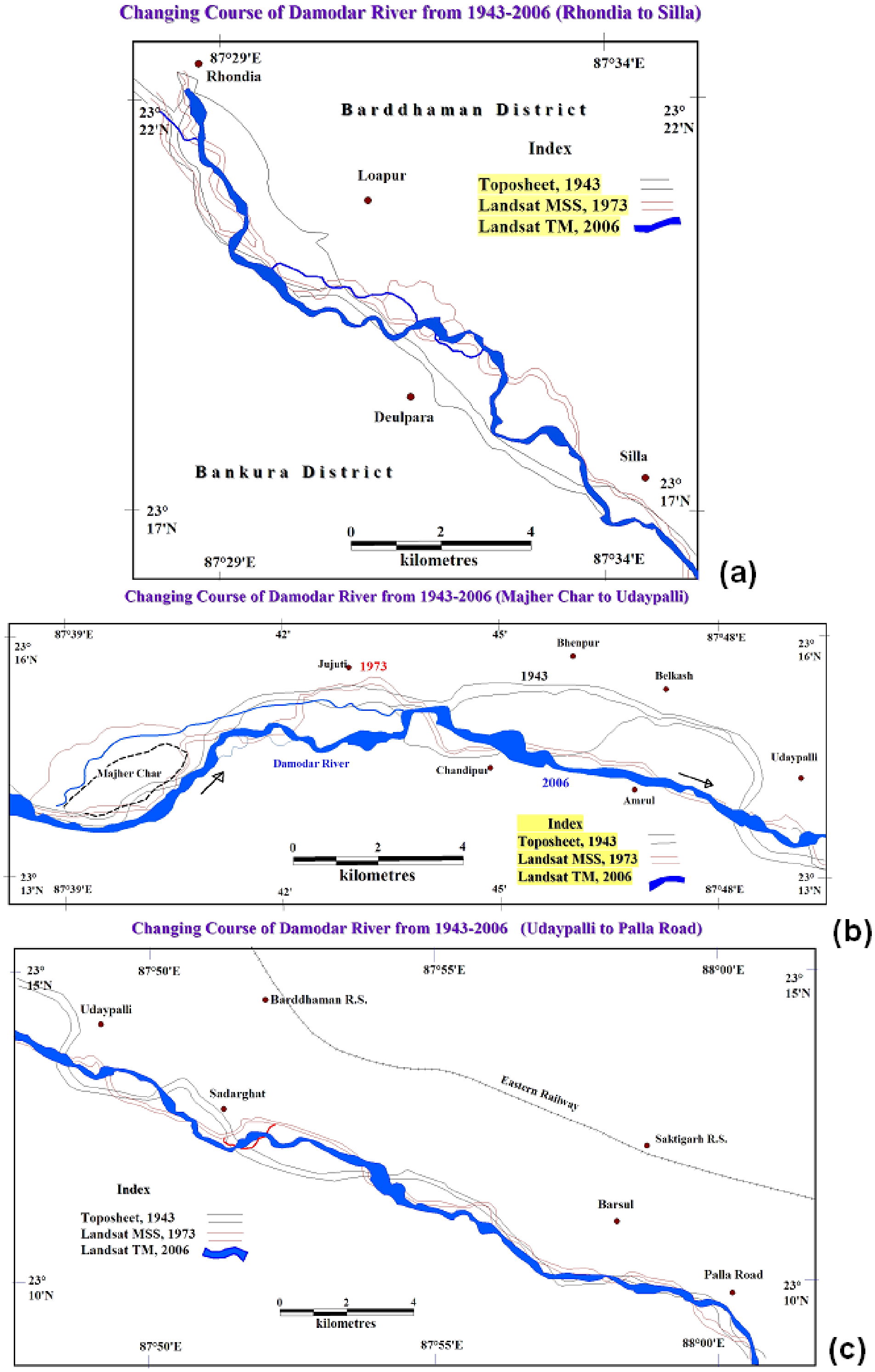

Figure 4: Changing courses of Damodar River showing the oscillation of thalweg in three reaches – (a) Rhondia to Silla, (b) Majher Char to Udaypalli and (c) Udaypalli to Palla (1943 – 2006)

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Near Silla, thalweg again shifts far south (meandering channel way) in 2006. That's why Damodar River gives birth of many longitudinal bars (locally named as '*char*') and islands (locally named as '*mana*') in mostly middle-left side, viz. Kasba Mana; Sadpur Mana etc. (figure 5).

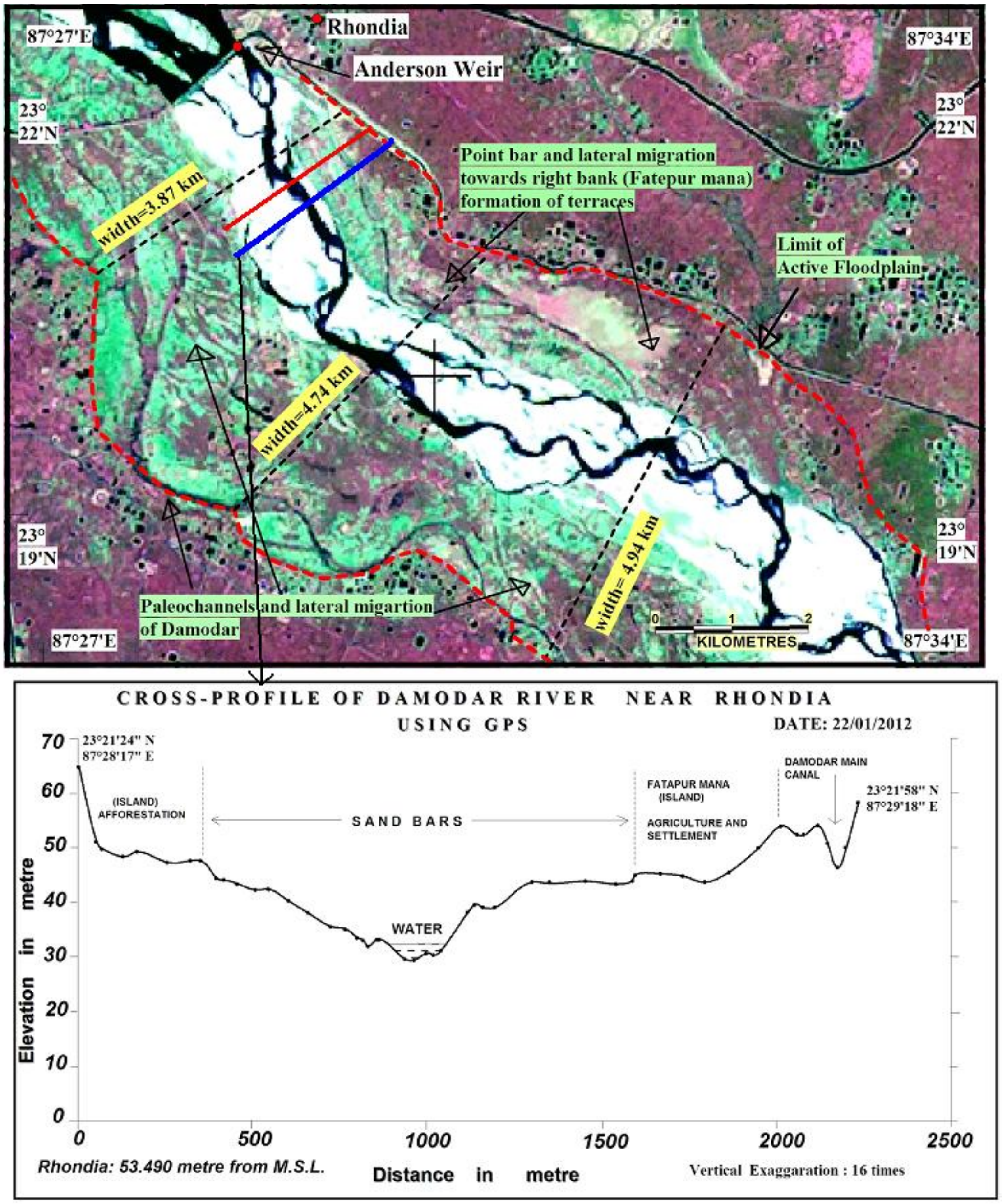

Figure 5: Development of wide floodplain, palaeochannels and point bars showing the degree of lateral migration and aggradation of Damodar River (Landsat ETM+, 2000) and GPS cross-profile of river showing confinement of valley within islands at Rhondia.

Research Article

Then, from the temporal observation of the reach in between Majher Char to Udaypalli, we have identified radical southward shifts of thalweg from Jujuti to Belkash, increasing its width of active valley (figure 4b and 6). Damodar flowed in 1943 very closed to Bhenpur and Belkash villages but after dam construction, its thalweg shifts further 1.0 - 1.6 km south nearer to Chandipur and Amrul villages (figure 4b). From GPS survey, we have depicted here a cross-profile near Jahapur village (near to Belkash), to show the shift of Damodar channel from left to right side (figure 6). It can be seen that from Chandipur Damodar maintains its straight course following Udaypalli than pre-dam period. In 1943, thalweg of Damodar was situated very near to Sadarghat, but after that it shifts right-side creating chars on left side. In compare to position of 1943 and 1973, in 2006 Damodar has tendency to go towards right side from Hatsimul to Palla.

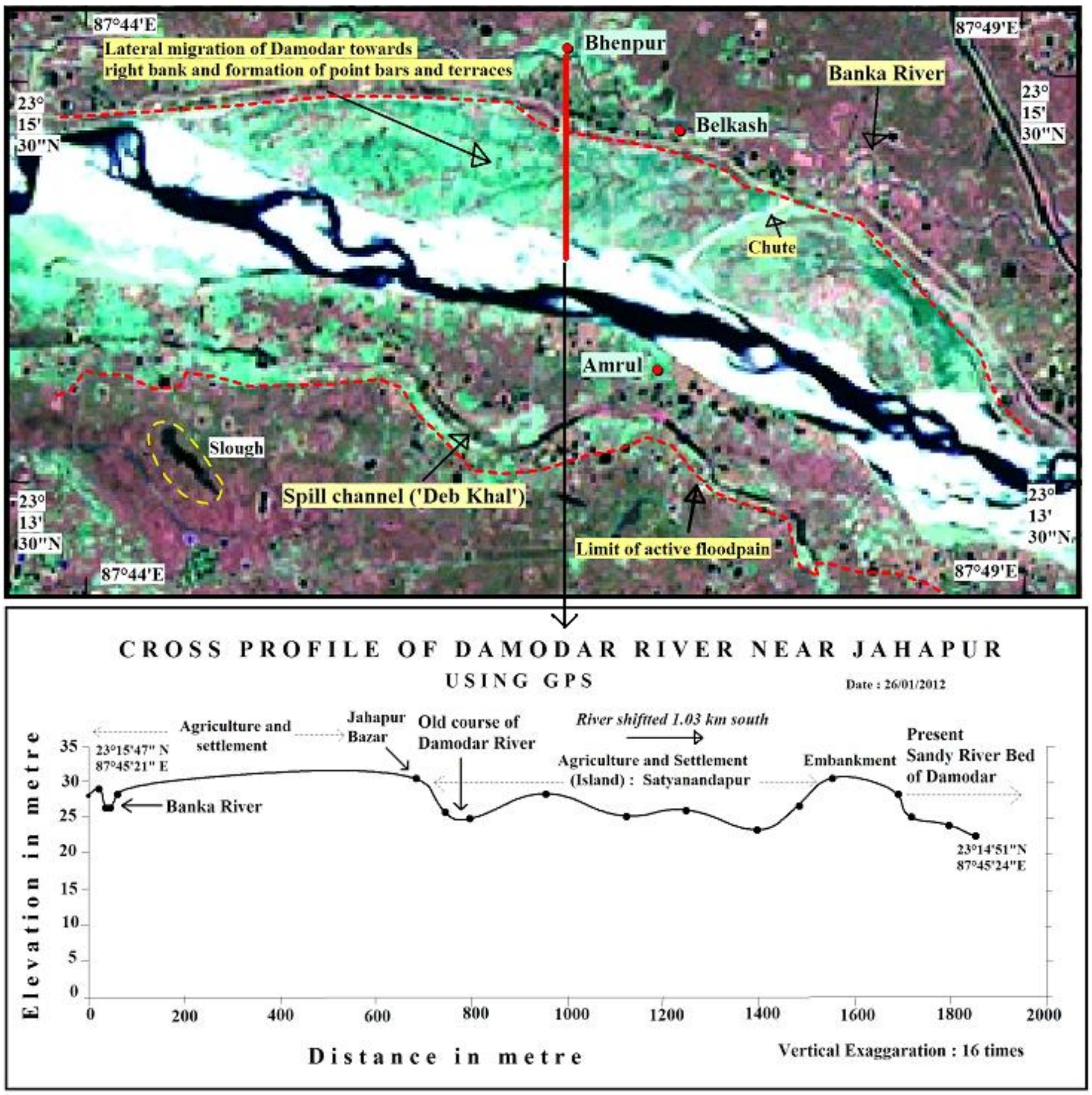

Figure 6: Development of wide floodplain, spill channels, sloughs and point bars showing the degree of lateral migration and aggradation of Damodar River (Landsat ETM+, 2000) and GPS cross-profile showing expanse of river shifting near Jahapur.

Research Article

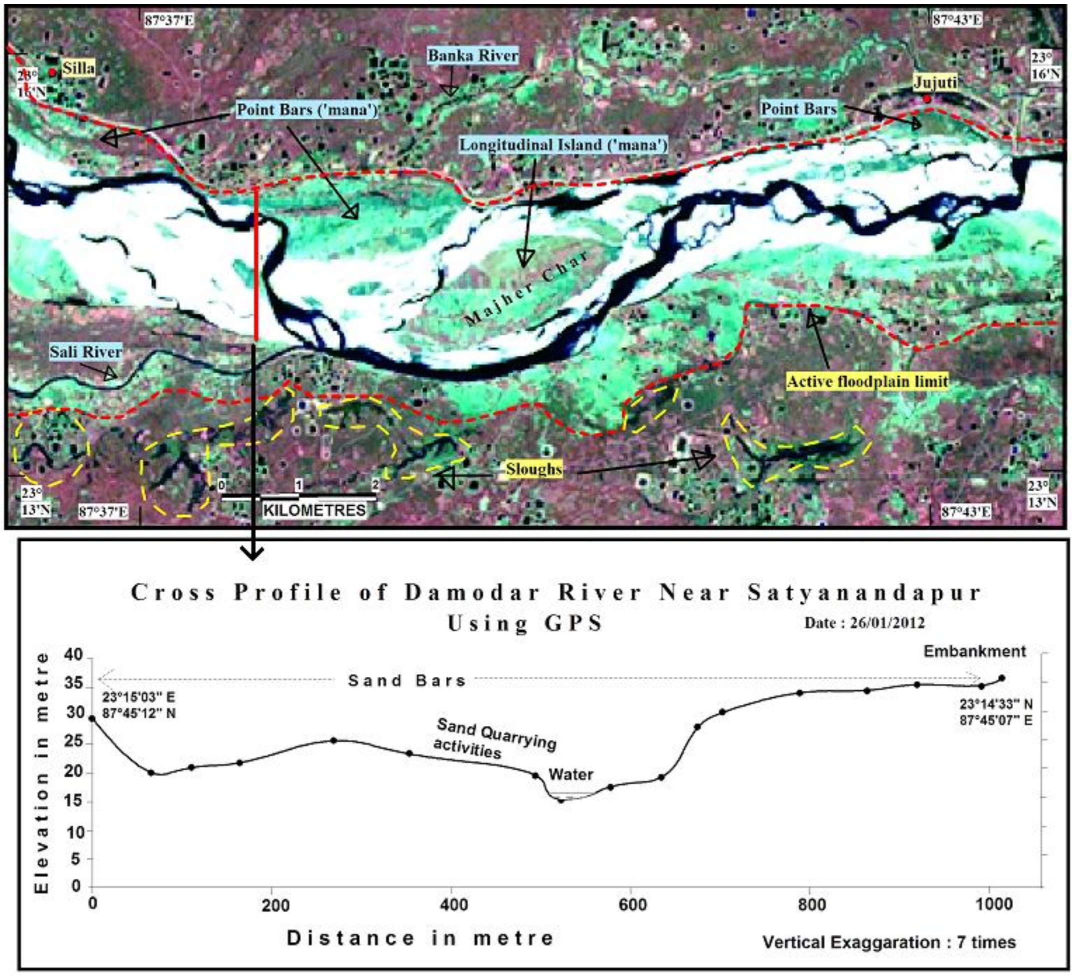

Figure 7: Development of wide floodplain, sloughs, point bars, islands and braiding showing the degree of lateral migration and aggradation of Damodar River (Landsat ETM+, 2000) and GPS cross-profile showing site of sand quarrying activities and left-bank erosion near Satyanandapur.

From this analysis it can be assumed that within embanked valley Damodar River now starts to oscillate within its constricted valley wall and mostly shifts its thalweg towards right-side. So the adjoining areas of right-side embankments (from Chandipur to Palla) are more vulnerable to bank erosion, flood erosion, overspill in peak discharge etc. It should be remembered that the flow of Damodar is regulated by dams and barrage, so hydraulic and topographic system of confined Damodar valley is continually adjusted its aggradation and degradation processes with this regulated flow and as a result, the River shifts its thalweg to maintain dynamic equilibrium within its system.

Identification of Fluvial Aggradation and Degradation

Now, three thematic maps are prepared to designate the post-dam temporal changes of both side embankments of Damodar River from Silla to Paikpara showing the variable expansion (erosion and deposition) of active valley in various sites from 1972. In this study, we have digitized both banks and channel from Landsat MSS (1972), TM (1990) and TM (2006) in three vector layers and after overlaying those we have depicted three final output maps for three reaches, viz. Silla to Jujuti, Sadar Ghat to Palla and Chanchai to Paikpara.

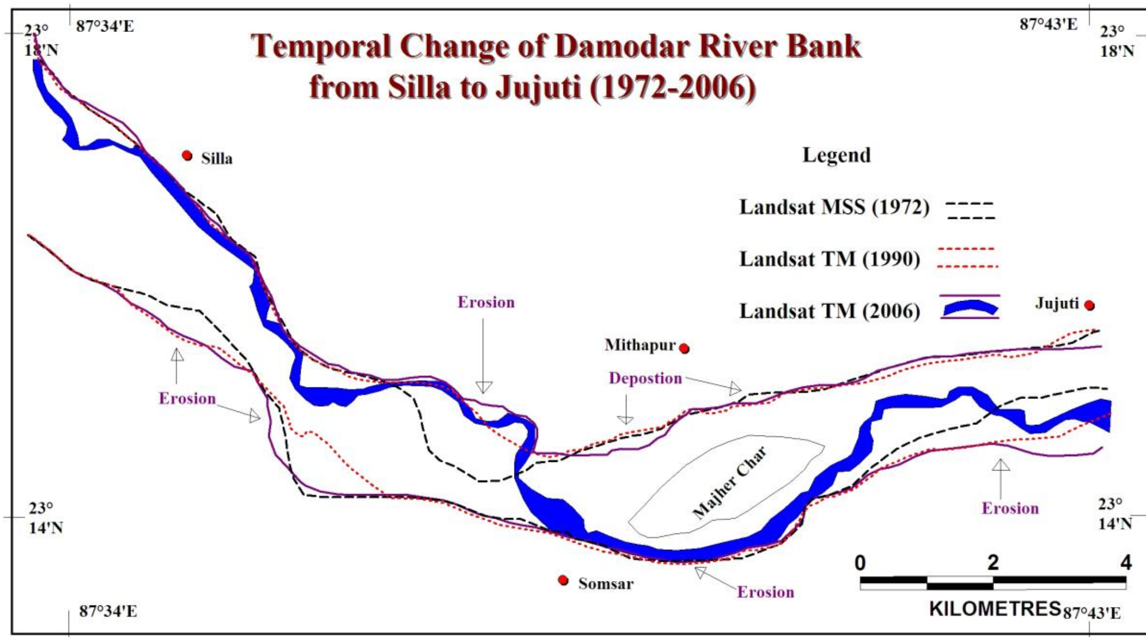

Figure 8: Temporal change of Damodar River banks from Silla and Jujuti (1972-2006)

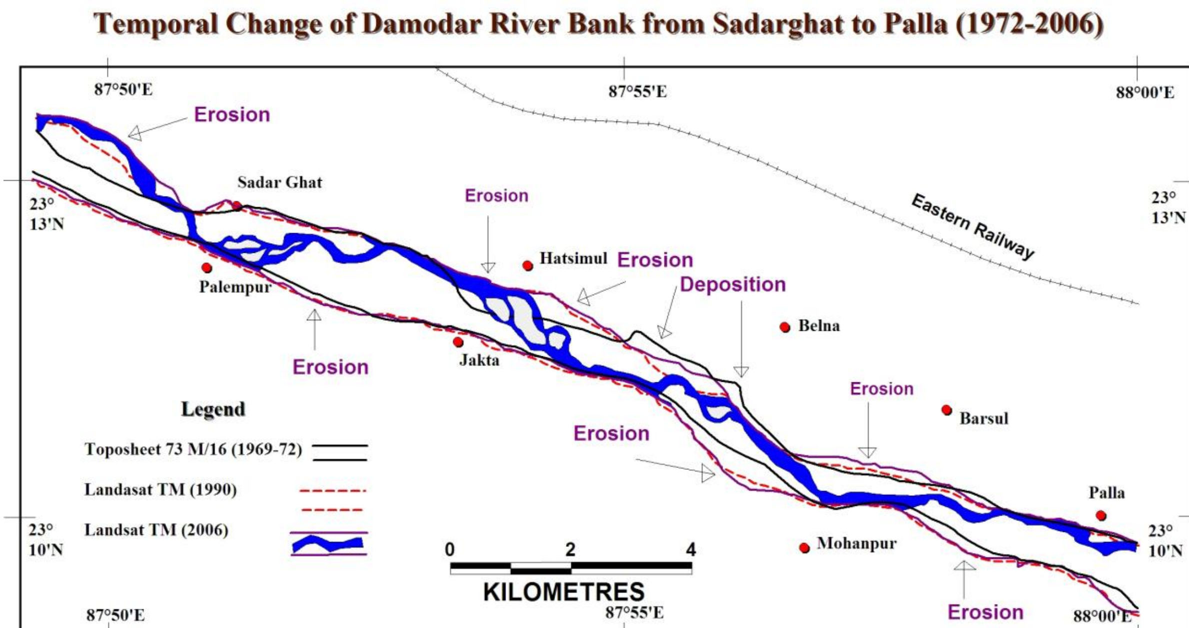

Figure 9: Temporal change of Damodar River banks from Sadarghat to Palla (1973-2006)

Below Silla village, Damodar turns easterly to Belkash, having wide valley. Here River shifts several times developing distributary of Bodai Nadi (meet with Sali Nadi) and few stagnant water courses on right side (near Deulpara, Deora, Tashuli, Panchpara etc.). Near Satyanandapur, in 1972 River was more constricted towards its right side, but in 1990 and 2006, Channel shifts to north nearer of left side embankment (figure 7). After that, it tends towards right side bank creating elongated Majher Char. The most vulnerable locations of bank erosion are Ghoradanga, Baikuthapur, Somsar, Beldanga, Dadpur (Bankura district) and Lakshmipur village (Barddhaman district).

After Majher Char, Damodar River enters into Barddhaman district and starts flowing in more or less straight pattern towards east up to Palla. It has been found that in 2006 Damodar erode its left side bars at Idilpur, but in 1972 the thalweg was confined towards right side embankment (Khalpara village) (figure 8). The flow is restricted near Sadarghat due to construction of Krishak Setu (Bridge). But after crossing the bridge, it opens up widely and erodes its right bank at Bangachha village. Then River erodes its left bank near Hatsimul and near Belna River thalweg shifts southward depositing coarse sediments on left-side. Near Barsul, Mohanpur, Birpur, Chak Krishnapur villages, the right-side embankment is susceptible to bank erosion (figure 9).

From Chanchai, Damodar turns right side towards permanently southward and surprisingly, its valley becomes narrower. Near Chanchai, there are signs of deposition but on opposite side right bank becomes wider in 2006 than 1972 due to erosion (figure 10d). The vulnerable sites of erosion (figure 10 a, b and c) are Berugram, Jamalpur, Jot Shriram, Fatehpur, Haragobindapur villages and the bifurcated course near Paikpara is completely dried up in 2006 due to sedimentation.

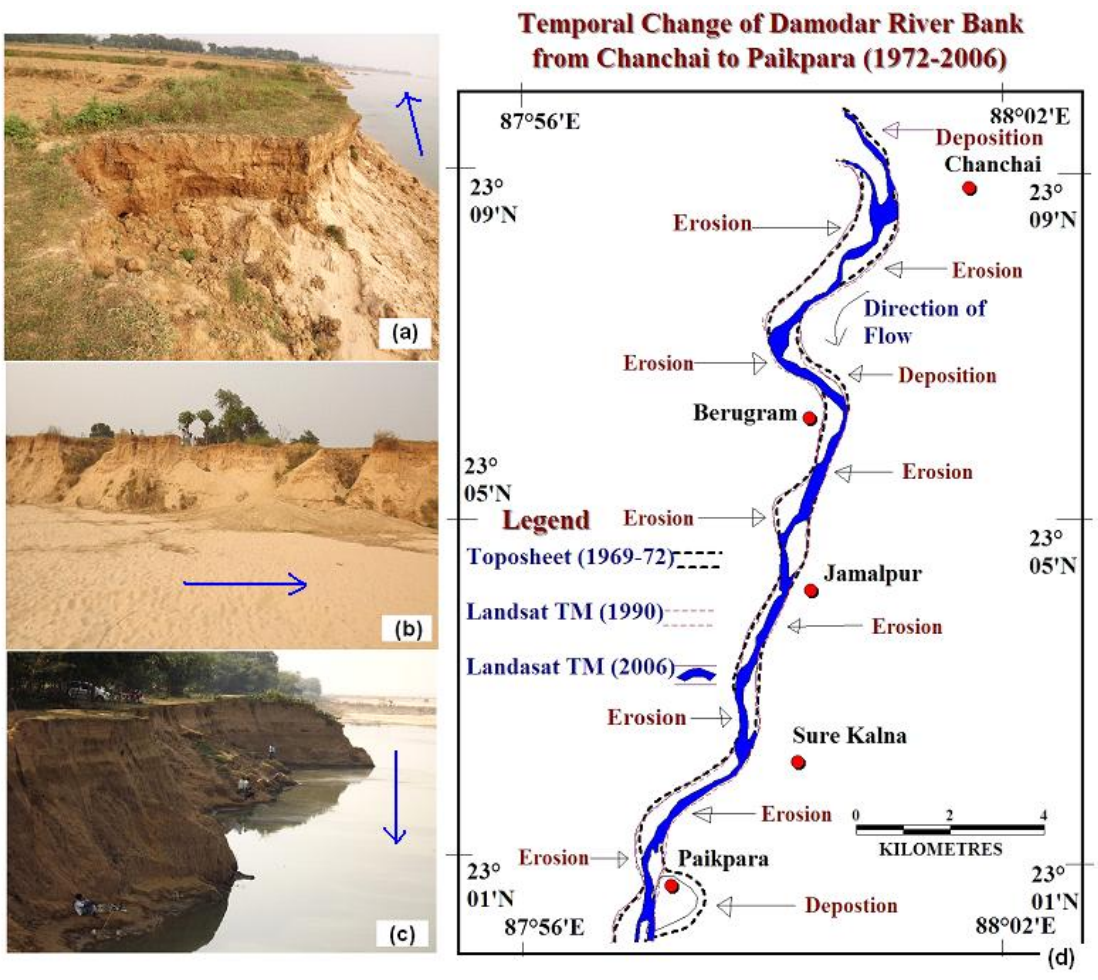

Figure 10: Glimpses of bank erosion at Idilpur (a), Belkash (2) and Amrun (c) (Note: blue coloured arrow indicates direction of flow) and (d) temporal change of Damodar River banks from Chanchai to Paikpara (1972-2006).

Research Article

Bank erosion though is very much less than pre-dam period but still now it is evident in few areas applying temporal satellite images and GIS. It was assumed that Damodar River was less moved after dam construction, but its movement is not restricted as evidence from images. Within its space of elevated embankments, River alters its active thalweg frequently in a meandering pattern and changes its aggradational and degradational processes in slip-off slope and cut-off slope. The areal change of left and right banks is depicted in following table to understand the possible average rate of bank erosion at six sites. In 44 years (1972-2006), the land lost, due to bank erosion of Damodar (table.1), are 0.73 km^2 (Natu), 1.36 km^2 (Idilpur), 1.10 km^2 (Hatsimul), 0.12 km^2 (Jankull), 2.23 km^2 (Dadpur) and 1.93 km^2 (Mohanpur) respectively. At Dadpur village (on right bank), the average rate of bank erosion ranges from 0.085 km^2 (1972-90) to 0.036 km^2 per year (1990-2006). Whereas at Idilpur site it varies from 0.035 km^2 (1972-90) to 0.04 km^2 (1990-2006) per year.

Table 1: Calculated eroded area of banks and rate of bank erosion from 1972 to 2006

	Estimated Eroded Area in km^2			
Nearest Village	**1972-1990**	**Average Rate of Erosion (km^2/year)**	**1990-2006**	**Average Rate of Erosion (km^2/year)**
Natu (right bank)	0.5410	0.027	0.1943	0.012
Idilpur (left bank)	0.7106	0.035	0.6467	0.040
Hatsimul (left bank)	0.8104	0.041	0.2942	0.018
Jankull (right bank)	0.0895	0.005	0.0273	0.002
Dadpur (right bank)	1.7110	0.086	0.5758	0.036
Mohanpur (left bank)	1.4170	0.071	0.5142	0.032

Sinuosity Index

For Mueller's sinosiuty index (1968), the four reaches are selected - (1) Rhondia to Kashpur (Bend I), (2) Kashpur to Idilpur (Bend II), (3) Idilpur to Chanchai (Bend III) and (4) Chanchai to Paikpara (Bend IV). In between 1990 and 2001 The Standard Sinuosity Index (SSI) varies from 1.0 to 1.15 in between Rhondia and Chanchai (table 2 and figure 11). It means the River widens its valley and developing bars within it and the sinuous channel is modified by high influence of hydraulic factors (60 to 74 percent) (Ghosh and Mistri, 2012b). In between 2001 and 2006 sinuous pattern of Damodar River is achieved from downstream to upstream direction and the most important fact is that Hydraulic Sinuosity Index (HSI) is radically increased in all four reaches (62 to 93 percent) in compare to Topographic Sinuosity Index (TSI) (7 to 38 percent). Especially in between Idilpur and Chanchai, HSI has contributed 92 percent influence on sinuosity and in between Chanchai and Paikpara, it is 85 percent. We have understood that the Damodar River is in transition phase between straight and sinuous, having few signs of braiding, i.e. lack of competence. Geomorphologically the straight stretches often occur in conjunction with or between bends or along braided reaches (Knighton, 1998). Even stretches with straight embanked banks have a sinuous thalweg pattern with asymmetrical shoals and point bars alternating along either bank, just like lower Damodar River (Ghosh and Mistri, 2012b). Post-dam changes in escalating SSI and HSI signifies that because of reduced sediment load downstream from a dam, the channel pattern of a river may be changed from braided to split or single thread, and may tend to become more sinuous (Bhattacharyya, 2011; Ghosh and Mistri, 2012b). Channel sinuosity appears to increase with water and sediment

Table 2: Mueller's Sinuosity Index (1968) of Lower Damodar River (Rhondia to Paikpara)

Rhondia to Paikpara	**Length in km**							
Year	CL	VL	Air	CI	VI	SSI	HSI (%)	TSI (%)
1943	91.23	87.13	64.16	1.42	1.35	1.04	15	85
1969-1972	91.00	84.50	64.16	1.41	1.31	1.07	24	76
1990	89.42	84.29	64.16	1.39	1.31	1.06	20	80
2001	94.53	85.97	64.16	1.47	1.34	1.10	28	72
2006	96.20	83.12	64.16	1.49	1.30	1.16	40	60

Note: CL = the length of the channel (thalweg) in the stream under study; VL = the valley length along a stream, the length of a line which is everywhere midway between the base of the valley walls (in this case one half of total length of right and left banks of a reach); Air = the shortest air distance between the source and mouth of the stream (in this case shortest air length of a reach); CI = Channel Index; VI = Valley Index; SSI = Standard Sinuosity Index; HSI = Hydraulic Sinuosity Index and TSI = Topographic Sinuosity Index.

discharge from straight to sinuous single channels, but then decreases towards the transition to braiding (Bridge, 2003). Streamflow below the control points (dams) has been reduced resulting in changes in channel morphology (increasing tendency of braiding in between Rhondia and Belkash) and the main cause of modification of channel pattern is the imbalance between the process of sediment transfer and energy dissipation in infrequent monsoon period (Garde, 2006; Bhattacharyya, 2011).

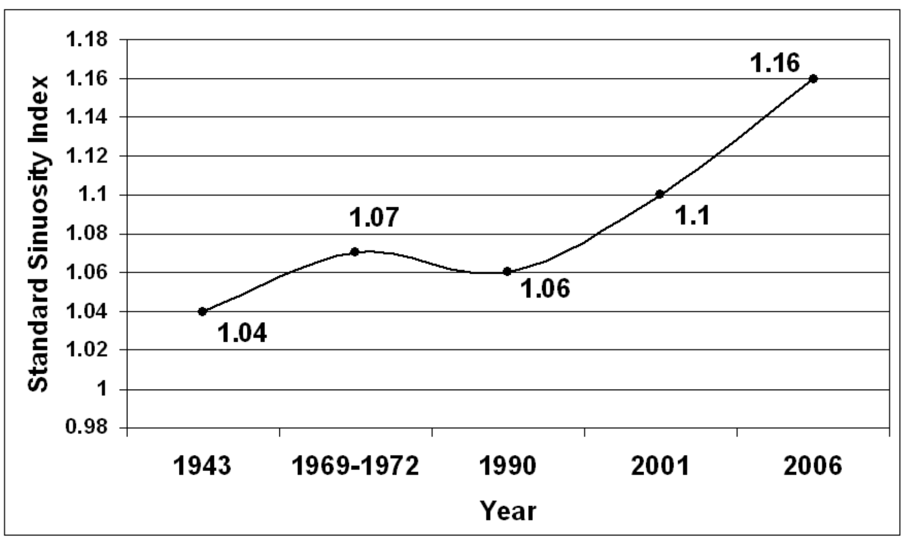

Figure 11: Increasing Trend of Standard Sinuosity Index (1943 to 2006) in Damodar River

Braiding Index

Brice's Braiding Index (BI) is a measure of the sum of island or bar lengths in a reach, and hence of the increase in bank length that results from braiding (Brice, 1964). This BI varies greatly with the water level and flow stage of main channel. The degree of braiding as displayed in toposheets and satellites

Table 3: Braiding Index (1990 and 2006) of selected bends of lower Damodar River

LANDSAT TM, 1990	**Length in km**					
Reach of Damodar River	L_i	L_r	L_{cmax}	L_{ctot}	**BI**	**BR**
Bend I (Rhondia to Kashpur)	44.31	16.68	18.63	45.98	5.31	2.47
Bend II (Kashpur to Idilpur)	65.60	27.82	30.33	83.48	4.72	2.75
Bend III (Idilpur to Chanchai)	27.05	18.85	19.90	40.57	2.87	2.04
LANDSAT TM, 2006	**Length in km**					
Reach of Damodar River	L_i	L_r	L_{cmax}	L_{ctot}	**BI**	**BR**
Bend I (Rhondia to Kashpur)	36.87	16.75	19.43	41.30	4.40	2.13
Bend II (Kashpur to Idilpur)	54.52	27.85	33.15	69.98	3.91	2.08
Bend III (Idilpur to Chanchai)	31.18	18.86	40.13	54.95	3.30	1.37

Note: *L_i = length of the islands or bars in a reach; L_r = reach measured midway between the banks of the channel; L_{ctot} = sum of mid-channel lengths of all the segments of primary channels in a reach; L_{cmax} = mid channel length of the widest channel through the reach; BI = Braiding Index (Brice, 1964) and BR = Braid-Channel Ratio (Friend and Sinha, 1993).*

images is well established by Braid-Channel Ratio (BR) which is devised and applied by P.F. Friend and R. Sinha (1993). It includes total sinuosity and divergent channel flows made by bars and islands. After a detail study of toposheets and satellite images we have been chosen Landsat TM images of 1990 and 2006 to calculate BR and BI. After that, we have selected the first three bends or reaches, viz. (1) Rhondia to Kashpur, (2) Kashpur to Idilpur, and (3) Idilpur to Chanchai for analysis, but in every map we have been obtained a single thread channel flow of Damodar from Chanchai to Paikpara, having very few divergence and convergence pattern (table 3).
As the values of BR do not reach to 'unity' (1), therefore, it identifies that three reaches have glimpses of braiding pattern (Knighton, 1998). The decreasing temporal variation of BI and BR is due to water level or stages of active channel area in 1990 and 2006. It does not mean that the degree of braiding is decreased from 1990 to 2006. We have stated earlier that this index is readily depended on flow stage of river when tops of bars are emerged at a particular time. BI of 1990 and 2006 ranges from 5.31 to 2.87 and 4.40 to 3.30 respectively. Similarly, BR of 1990 has a highest value of 2.75 on bend II and lowest value of 2.04 on bend III. Again BR of 2006 has a highest value of 2.13 on bend I and lowest value of 1.37 on bend III. Increasing numbers and lengths of longitudinal, point and linguoid bars are responsible for more braiding between Rhondia and Idilpur. It appears that braiding of Damodar River is a type of hydraulic adjustment that may be made in a channel possessing a particular or coarse bank material in response to a debris load too large to be carried by a single channel (Wolman and Leopold, 1957; Garde, 2006). Braiding and avulsion are interlinked in the alluvial floodplains. It is observed that Damodar River had been shifted its course further south (>1 km) near Rhondia and Idilpur, forming mature islands and bars on left side (figure 6).

DISCUSSION

The phenomenon of fluvial degradation ocurrs when the upstream sediment load being transpoted by Damodar River is less than sediment transporting capacity of the river and the excess sediment needed to satify the capacity of Damodar River will be scoured from erodible river bed and banks (Gregory and Walling, 1973; Knighton, 1998 Bridge, 2003). Late Holocene channel aggadation followed a period of high sediment supply in the Ganga delta (Bengal Basin), suggesting that depostion reflected transport-limited condition of Damodar River Basin is the amount of transported load is limited by water supplied to the river (Roy *et al.*, 2012). Degradtion results in channel incision and often this phenomenon forms assymetric terraces (remained as mature points bars) on both sides. This is observed downstream of Rhondia Anderson Weir, Silla, Jujuti, Belkash, Hatsimul, Chanchai and Jamalpur. When the sediment transporting capacity of a river at a point becomes less than the sediment laod being carried, as aresult of reduction the velocity due to an increase in cross section or reduction in the slope of the river, the excess sediment get deposited on Damodar River bed (Gregory and Walling, 1973; Knighton, 1998 Bridge, 2003). Aggadation of Damodar River also occur in selected reach due to high sediment load coming from Chotanagpur Plateau being conveyed to the river increses than that can be carried by the river in equlibrium. As a result the river bed of Silla, Jujuti, Majher Char and Belkash rises and forrces the channel to carve out its path in a braided fashion and occasionally avulsion of main path. The rigouus sand quarrying acativities (creating deep hollows) on river bed increses flow accelaration in monsoon months (due to silation of river bed and decreasing downstream cross-sectional area) coupled with current deflection around point bars, trigger bank erosion (Chakraborty *et al.,* 2011; Bhattacharyya, 2011; Ghosh and Mistri, 2012b).

The total reach under study is controlled by upstream dams, barrages and weirs, rendering its oscillation within its embanked lower valley. Damodar River is relatively behaving as confined braiding where there is a well defined channel way that fills with water during floods and develops a pattern of submerged bars. As flood stage decreases, the bar tops emerge, producing a braided channel pattern. Braiding intensities are decreased towards downstream, as channel area becomes narrower. The average cross sectional areas of three reaches are 0.071, 0.043 and 0.0187 km^2 respectively. The average width-depth ratios of three braided reaches are 35.43, 39.96 and 39.19 respectively (based on SRTM elevation data, 2006). The braiding of Damodar River is due to moderate slope and high bed roughness with aggradation of sand or coarse bed materials.

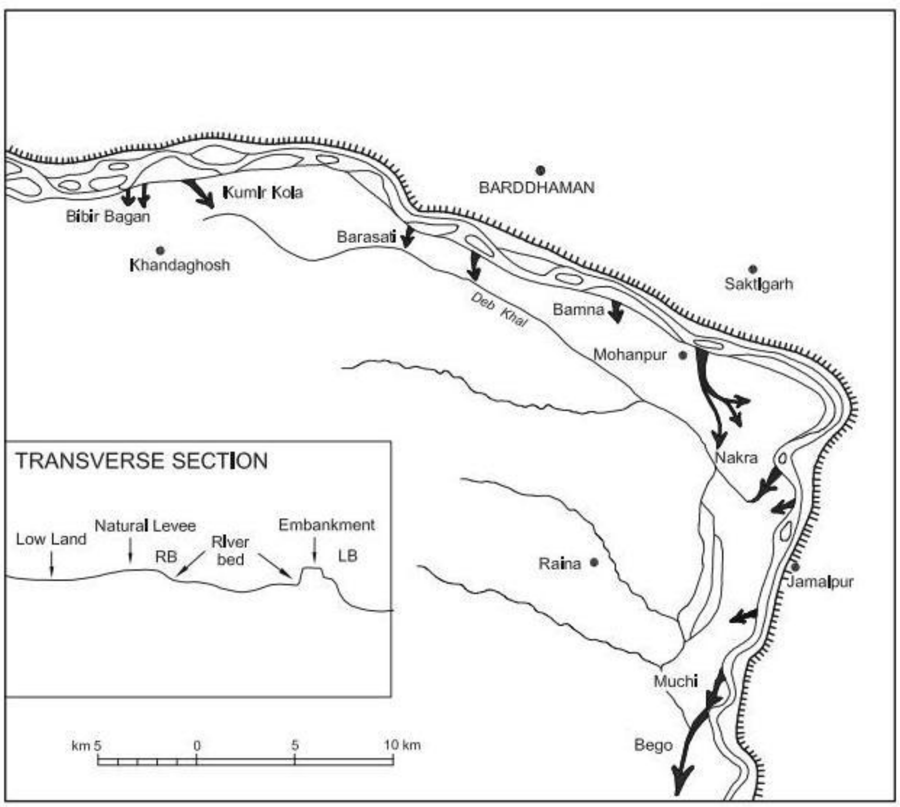

Figure 12: Glimpses of spill channels of lower Damodar River denoting the sites of embankment breaching on right side *(Source: Bhattacharyya, 2011)*

As studies done by Sen (1985, 1991), Garde (2006) and Bhattacharyya (2011) bankfull discharge, variable flow velocity, fluctuating monsoonal flow regime, high hydraulic radius of channel, channel bed roughness, turbulent monsoonal river flow including eddies, coarse sand bed and vegetation growth on bars and banks, low sediment supply due to trap efficiency of upper catchment reservoirs, elevated concrete embankments and flow diversion through canals are regarded as the dominant hydraulic factors to deviate channel sinuosity in the downstream section (Ghosh and Mistri, 2012b).

From the above analysis of important maps, it is quite understand that bank erosion is a problem of lower Damodar River. In those areas, rigorous sand quarrying and agricultural activities on charlands and manas (i.e. bars and islands) are aggravated bank erosion problem (Bhattacharyya, 2011). So the identified locations can be transformed into weakest sites for next shifts of channels, overspill, embankment breaching and flood inundation. To adjust with heavy flood flow or peak discharge, River will compel to choose those locations to release its excess water over the levee, because as the River goes downstream from Barsul village its cross-sectional valley area and capacity of water storage is gradually reduced (Chakraborty *et al.*, 2011). Therefore, those locations should get immediate attention for flood and bank protection measures. Side by side, Damodar River has tendency to breach its right bank at numerous points in peak discharge and overflow had been created many spill channels, locally named as '*Hanas', viz. Deb Khal* (figure 12). Recently, Damodar River overflows its right bank on 10th August, 2011 in the adjoining villages of Barjora, Sonamukhi and Patrasayer blocks (Bankura district) due to release of only 25,000 cusec water from Durgapur Barrage.

Conclusion

The employed methodology is found to be significant in this research work, providing remarkable spatio-temporal information about fluvial landforms and processes. Integration of remote sensing, GIS and quantitative geomorphology has identified the present sites of fluvial deposition and erosion in selected reaches of Damodar River. Damodar River is regarded as mixed suspended and bed load channel, having 30 – 65 percent of silt-clay on channel perimeter and high width to depth ratio (> 40). In that reason sinuosity index is less than 1.3 and channel slope is low to transport all bed loads, maintaining meandering thalweg to dissipate less energy. Braiding of Damodar River is well associated with variable discharge and incompetent to bed load. But braiding is not indicative of excessive bed load since aggradation can take place at constant slope without braiding. This means braiding is not a matter of lack of capacity but lack of competence. Current increasing sinuous and braiding pattern of lower reach is the consequence of mutual interaction in between sudden peak monsoonal discharge and flood controlling actions of DVC authority, including the riparian anthropogenic activities, viz. sand quarrying, bridges, concrete left embankments, bank side intensive agriculture and grasping of bars and islands for agricultural uses and settlement. Up to Barddhman town we have noticed numerous developments of point and mid-channel bars, having abandoned palaeochannels and terraces of Mid Holocene. Below Barsul the narrowing of river occurs through the formation of in-channels berms or benches at the margins. With narrowing and increasing sinuosity (below Chanchai) Damodar River now intends to move freely along its confined valley through its increasing percentage of hydraulic activities (equilibrium in lateral erosion and valley incision) and bank erosion is accelerated in the period of peak monsoon.

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