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Analyzing fluvial hydrological estimates and flood geomorphology from channel dimensions using ASTER DEM, GIS and statistics in the controlled Damodar river, India

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Abstract: The Damodar river of eastern India has good physiographic and hydrogeomorphic potenial of extreme floods because the entire basin is situated in the major rain-storm zone of Bay of Bengal. Since 1950s Damodar Valley Corporation (DVC) of India has constructed a number of large and medium sized dams on the upstream tributaries of Damodar catchment to regulate floods and at the same time for different purposes especially agriculture to utilize water. But with the passage of time, the DVC controlled lower Damodar river has lost its previous capacity to accommodate excess water within its active limit, and at the time of peak monsoon and strong depression excess water (released from dams and barrage) occasionally overflows its banks in the lower floodplain of basin (covering the districts of Barddhaman, Hooghly and Howrah). So it is essential to estimate and calculate the current hydrogeomorphic status of lower Damodar at the ungauaged sites, treating each channel segment as a fluvial unit. Using recent satellite data, statistics and GIS, the present paper has tried to quantify various channel dimensions (viz. width-depth ratio, bankfull width, bankfull cross-section, entrenchment ratio, sinuosity, gauge heights etc.) and variability of potential bankfull and maximum discharges at very micro scale (i.e. cross-section and channel reach) between Rhondia (23°22´08´´ N, 87°28´25´´ E) and Paikpara (23°00´58´´ N, 87°57´41´´ E). The ultimate result of multivariate analysis suggests that with downstream increase of channel distance the Damodar river has changed from braiding to confined meandering pattern with significant loss of bankfull width, bankfull area, volume and bankfull discharge which reflects an increasing vulnerability of flood risk in near future.

Keywords: Channel dimension, Bankfull discharge, Flood, ASTER, PCA, Damodar river

1. Introduction

Flood is the only major natural hazard in India that occurs with an unfailing regularity. It normally occurs after a spell of heavy rains, which may last for a period of several hours to several days that generate huge runoff in the catchments and the rivers experience floods (Kale, 2003). During prolonged monsoon rainfall (June – October), flooding is the natural mechanism by which excess runoff is removed from the channel and occasionally it overflows. Thus it is very important to realize that the floods are inevitable in a fluvial system of tropical climate and they are expected to be repetitive (Sinha, 2011). Realyzing the erratic nature of monsoon and climate change, a question of fundamental importance in flood hydrology and geomorphology is studying the pattern of change in the flood behaviours and hydrogeomorphology of Indian rivers in future (Kale, 1999). The recent literatures on the flood hydrology and geomorphology are dominated by (1) studies on the spatio-temporal aspects of floods, (2) research on the impact of floods in bed-rock and alluvial rivers, (3) research on the impact of river engineering structures on flood propensity, (4) studies on palaeofloods of western and central India, and (5) remote sensing and GIS (Geographic Information System) based fluvial research (Rao, 1951; Rajaguru et al, 2005; Kale 1998, 1999, 2003 and 2005; Sinha and Jain, 1998; Mishra, 2001; Rakhecha, 2002; Nandargi and Dhar, 2003). But the micro to meso scale fluvial study, focusing on current status of channel dimensions and discharge at ungauged stations or any locations is, to some extent, lacking in the literatures of Indian geomorphology and flood studies. This type of measurement and estimation is very much applicable in the study of flood risk assessment. It is observed that the cyclonic circumstances of Bay of Bengal and other favourable ground conditions help in generating prolonged rainfall and high percentage of runoff in the upper catchments of peninsular rivers (viz., Brahmani, Dwarka, Mayurakshi, Ajay, Damodar, Dwarkeswar, Silai and Kangsabati etc.) because of the antecedent wet conditions caused by unexpected rainy spells occurring during the monsoon period itself (Rao, 1951; Dhar and Nandargi, 2003). It has been found that the entire catchment of Damodar river lies in the major rainstorm zone of lower Gangetic plain and its flash-flood magnitude index is much higher than other Indian rivers, viz., Ganga, Satluj, Brahmaputra, Teesta, Narmada, Kosi etc. (Kale, 2003). During 1950 – 59 the floods of Damodar river were regulated and controlled by the upstream dams, barrage, embankments and canal system but still it has high potenial of moderate to extreme floods in the monsoon period (June – October). Due to installation of hard engineering structures by DVC (Damodar Valley Corporation) authority and rigorous riparian anthropogenic activities (i.e. sand mining, bridges and agriculture), the middle to lower part of Damodar valley (situated in Barddhaman, Hooghly and Howrah districts) has been affected by floods in 1959, 1978, 1995, 2000, 2006, 2007, 2009, 2011 and 2013 (Bhattacharyya, 2011; Sanyal et al., 2013). This fact has raised two important queries in mind –

(1) A statistically significant increase in the number of flood victims during same period, suggesting excess development and rapid population growth in flood-prone areas – causing high vulnerability; and

(2) The accommodating capacity of upstream dams, barrages, canals and Damodar river itself are declining to store or pass the excess monsoon runoff within their limit, mainly due to siltation and aggradation.

Both the statements are scientifically justified and it compels to think about the current status of channel geometry and bankfull discharge which can be recommended as intrinsic threshold (Schumm, 1985) in respect of existing channel morphology of Damodar river. DVC authority and IWD (Irrigation and Waterways Department, Government of West Bengal) had set forth the critical limit of discharge at Rhondia and gauge heights at few sites more than fifty years ago but observing the dynamicity of this alluvial river and aggradation of river bed it is very essential to quantify the current channel dimensions and potential bankfull or peak discharges at various channel segments to forecast floods accurately. It can be taken as a measure by DVC and IWD about the exact amount of discharge to be released safely along the channel. Focusing all the hydrological aspects and using the satellite data, the present paper attempts to quantify the current status of channel dimensions and variability of potential discharge in the lower segments of Damodar river. Attempts have been made to classify the channel reaches of Damodar river to highlight the resultant interaction between the monsoon sediment transport and present channel dimensions.

2. Geographical facets of controlled Damodar river

The river Damodar, historically known as the 'river of sorrow' or 'sorrow of Bengal' (Bhattacharyya, 2011), was characterized by its annual occurrence of massive floods in the lower basin (i.e. southern West Bengal) till the pre-dam period (up to 1957). W. W. Hunter regarded those floods as 'harka ban' (i.e. flash flood) with giant wave of 1.5 m height (Lahiri-Dutt, 2006). Though this has not yet strongly outlived the hazards of extreme floods during the last two decades of the post-dam episode (Sen, 1985). The furious Damodar river originates from the Khamarpat Hill of Chandwa CD block (Palamau district, Jharkhand) and is one of the longest east flowing rivers (542 km length) of Chotanagpur Plateau (figure 1), having basin area of 23,300 km^2 (Sen, 1985; Chandra, 2003; Bhattacharyya, 2011). Downstream of Asansol City the river crosses the hindrances of Durgapur barrage and Anderson weir, and after that it flows almost straight up to Barsul village, traversing the Laterite Rarh plain (Early Pleistocene Formation), the Sijua formation (Older Alluvium – Late Pleistocene to Early Holocene) and Chuchura formation (Newer Alluvium – Mid to Late Holocene) (Niyogi et al., 1970; Bhattacharya and Dhar, 2005). The straightness of course or low sinuosity of lower Damodar is the direct result of three successive major basement faults: (1) Chotanagpur Foot-hill fault, (2) Medinipur – Farraka fault and (3) Damodar fault (Singh et al., 1998). For sample study we have selected the lower reach of Damodar river between Rhondia (Galsi I CD Block) and Paikpara (Jamalpur CD Block). The latitudinal extension of selected area ranges from 22° 00′ to 23° 22′ N and longitudinal extension varies from 87°28′ to 88°01′ E.

Figure 1: (a) Spatial extent of Damodar river basin in the states of Jharkhand and West Bengal, and (b) ASTER elevation map of study area, including sample locations of field survey along the Damodar river

With the direct initiatives of Dr. Meghnad Saha and W. L. Voorduin the DVC came into existence on 7th July, 1948 to develop an integrated multipurpose plan, constructing the large dams of Tilaiya, Konar, Maithon, Panchet, Durgapur Barrage and Tenughta (Chandra, 2003). Under the DVC and lower Damodar scheme of IWD, entire downstream segment of Damodar river is forced to transform from a natural channel to a 'reservoir channel' to manage recurrent floods (Sen, 1991; Bhattacharyya, 2011). DVC and IWD established macro to micro control measures of flood protection with modification through deepening, widening and straightening of channel, jacketing the river with multi-level embankments, drainage diversion through canals up to storing and releasing water through weir, sluices, barrage and reservoirs.

According to Bhattacharyya (2011) and Sanyal et al. (2013), the Damodar river can be regarded as a ‘controlled river’ because its discharge, sediment transport and deposition and other fluvial behaviours are influenced and controlled by the engineering structures.

3. Material and methods

In this context the constructivist (building block) approach to analyze the fluvial landscape is adopted here to assess functionality of each part of fluvial system relating with major channel dimensions and geometry. This ‘bottom up approach’ (Fryirs and Brierley, 2013) synthesizes the behaviour of fluvial components and evolution of landforms through systematic analysis of channel segment treating each reach as individual unit of study (figure 2).

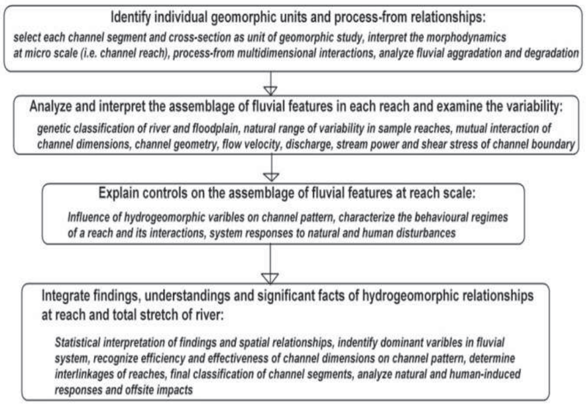

Figure 2: Constructivist bottom up approach to fluvial study, applied in this analysis (after Fryirs and Brierley, 2013)

Uncertainty of physical event is very much allied with high monsoon rainfall, runoff generation and flash floods but if we estimate the current status of flood flow or bankfull discharge or water accommodation capacity of channel segment then an idea of emergent flood risk can be found with some quantitative judgments. The long continuous, up to date and reliable hydrological records and geomorphic data are an indispensable part in the study of changing fluvial dynamics and flood risk assessment. The secondary hydrogeomorphic data and other spatial information are mostly collected from the writings of Chatterjee (1969) and Bhattacharyya (2011), official website of Irrigation and Waterways Department of West Bengal (IWD), topographical sheets of R.F. 1: 50,000 (73 M/7, M/11, M/12, M/15, M/16, N/13 and 79 A/4) of Survey of India (SOI), ASTER data (2011), satellite images of IRS-P6 LISS IV (2008) and Google Earth (2013). ASTER elevation data is mostly used to calculate various channel dimensions and the satellite images are used to get a synoptic view of the study area with its permanent spatial references.

Following hydrogeomorphic approach to fluvial study, an individual river can vary significantly downstream, changing its channel dimensions and pattern dramatically over a short distance. Reaches are singular because of the numerous variables acting that prevent a single variable, discharge, from dominating river morphology and behaviour (Leopold and Miller, 1960; Schumm, 2005). Here the main spatial unit of study is channel reach. The quantitative channel morphology is derived from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data which has five remote sensory devices on the board of Terra satellite launched into earth orbit by NASA (National Aeronautics and Space Administration) in 1999 (USGS; United States Geological Survey, 2013). The Global Digital Elevation Model (GDEM) of ASTER was released to the public having spatial resolution of 30 m (USGS, 2013). So using processed ASTER DEM (Digital Elevation Model) data (2011, http://earthexplorer.usgs.gov/), Global Mapper 14.2 software (technique of 3D path analysis and cut and fill volumes) and ArcGIS 9.3 software for at least 25 cross-profiles, as representative ungauaged sites of Damodar river (figure 3) are taken between Anderson weir, Rhondia (last water releasing controlled point) and Paikpara (bifurcation point – Damodar and Mundeswari).

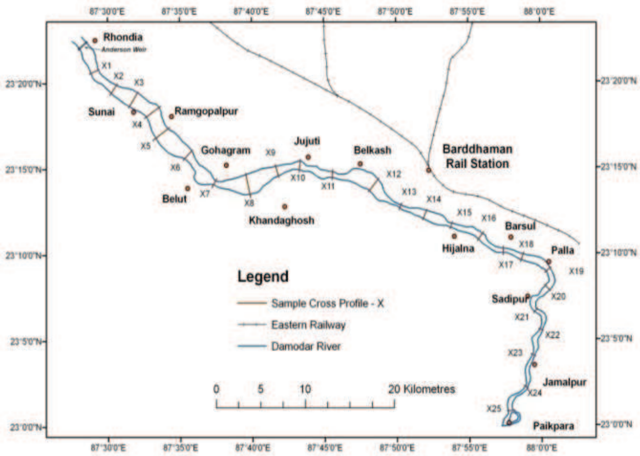

Figure 3: Sample cross-profiles taken across the Damodar river in between Rhondia and Paikpara

Here quantification of channel dimensions mainly includes channel cross-sectional area (A_b), volume of that cross-section (V_c), bankfull width (W_b), maximum depth (i.e. thalweg depth) of that profile (D_{max}) and width – depth ratio (W/D). All morphological and statistical analysis is done towards downstream segment from Rhondia to explain the variations with flow direction. As the river is seasonally dry or single-thread channel in winter and summer, the ASTER data of December is very useful to study the channel-bed morphology (figure 4).

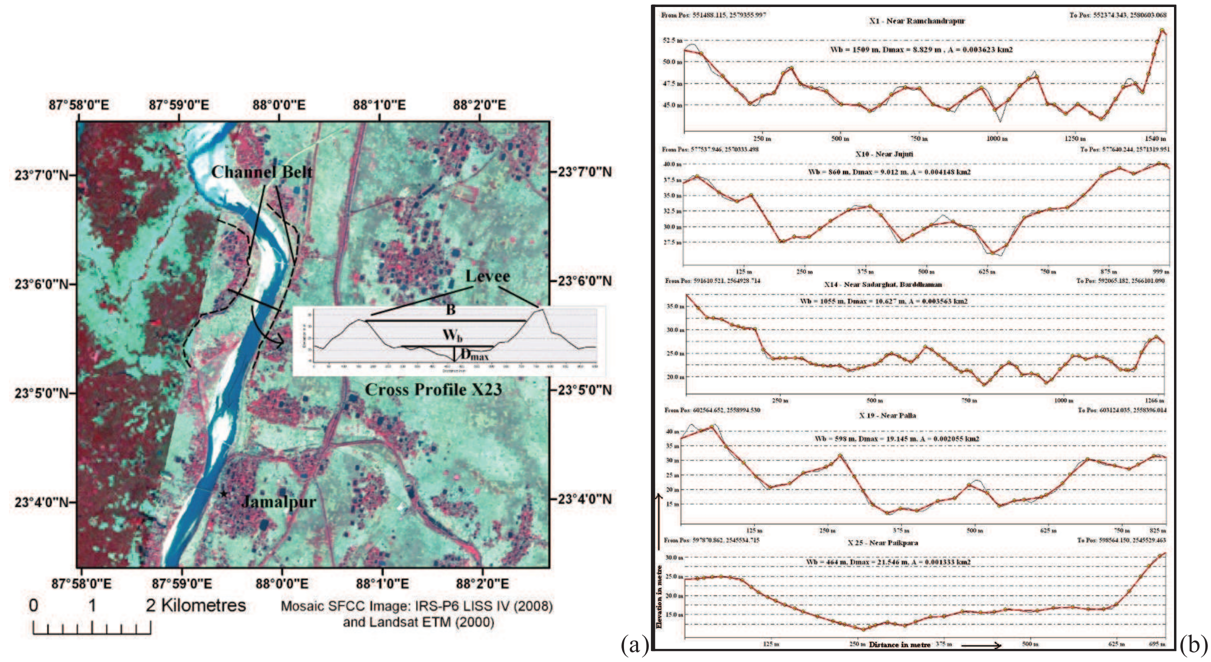

Figure 4: (a) Sample estimation of channel dimensions at X23 using satellite image and ASTER cross-profile; and (b) selected downstream cross-sectional profiles (X – distance in m and Y – elevation in m) of Damodar river at X1 (near Rhondia), X10 (near Jujuti), X14 (near Sadarghat, Barddhaman), X19 (near Palla) and X25 (near Paikpara (Note: the profiles are prepared from the ASTER DEM using 3D tools of Global Mapper 14.2 software)

The method of volume estimation specifies the base heights of the cross-section (option of above the ground – the base height will be relative to ground level at each vertex in the line with Datum of WGS-84) which are identified by the GIS through the maximum number of sample nodes or vertex along the section. In the output graph of cross-section, any area higher than this height is used as cut volume and any area below this height is used as fill volume. The total workflow of the research is depicted in flowchart (figure 5).

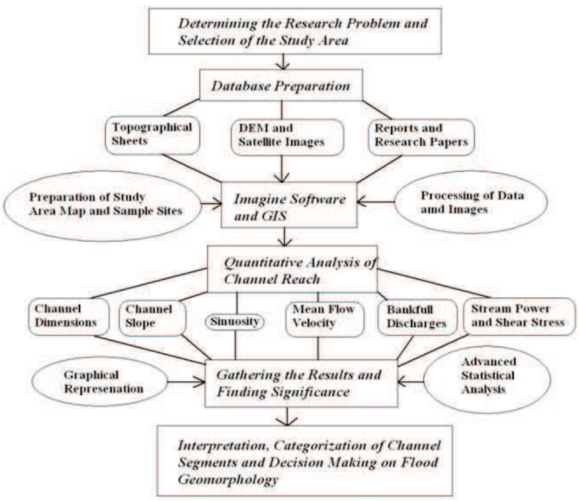

Figure 5: Flowchart of methodology applied in this study

The methods for reconstructing the morphology and hydrology employ several groups of empirical relationships derived dynamic models of fluvial flow and sediment transport in the alluvial reaches (Schumm, 1968; Williams, 1988; Khan and Tewari, 2011). In recent years, fluvial sedimentologists have carried out numerous studies to estimate quantitative hydrodynamics of ancient fluvial systems, particularly, their morphology and hydrology using palaeohydrological approach (Gregory, 2003; Kale et al, 2004; Garde, 2006; Baker, 2008). The empirical relationships (developed by Allen, 1970; Leeder, 1973; Rotnicki, 1983, Williams, 1988, Pickup and Warner, 1983; Kale et al., 2004) among channel dimensions, planform characteristics and discharge have been compared and applied to derive the present hydrogeomorphic individuality of the controlled Damodar river. The important statistical techniques, viz. mean, standard deviation, standard error of estimate, confidence limit, Pearson's product moment correlation, linear and non-linear regression, coefficient of determination, *t* – test, Principal Component Analysis (PCA) and Z-score etc. (Mahmood, 2007; Kothari, 2009) are employed here to derive significant conclusion about the fluvial dynamics of alluvial river.

4. Result and discussion

4.1 Fluvial hydrological estimates and statistical significance

Geomorphic parameters such as channel patterns, meander characteristics and palaeochannels dimensions were first used in palaeohydrology by Leopold and Miller (1954), Dury (1954, 1976) and Schumm (1965, 1968, 1977) and were successively modified depending upon their area of application (Tinkler 1971; Patton and Baker, 1977; Knox, 1985; Williams, 1988; Garde, 2006). Fluvial hydrology includes the interaction of channel planform and inherent characters (i.e. width, depth, slope, sinuosity, sediment, channel roughness, channel geometry etc.) with river hydraulics (i.e. discharge characteristics and flow patterns) and hydrological parameters (Ward, 1978; Garde, 2006).

Not uncommonly, the researchers inadvisedly have tried to circumvent this problem by estimation or guessing values for the required input variables and then inserting those estimates into an empirical equation to determine a channel dimension (Williams, 1988). Thereafter, according to Williams (1978, 1986, 1988) the preferred alternative is to utilize values that have been measured than estimated, for example, channel dimensions or channel characteristics at the ungauged sites (table 1).

Table 1: Estimated channel dimensions and other characteristics of Damodar river

Sections	A_b	W_b	D_{max}	W_b/D_{max}	B	F_p	ER	Si	S	R	Q_{max}	Q_b	V_c	M	τ	ω Q_b	ω Q_{max}
	36	15	8.8	170.9	106	469	3.1	1.1	0.000	2.4	4889.	3032.	21.3	1.4	8.6	7.2	11.6
X1	23	09	29	1	67	3.2	1	45	367	01	25	58	25	4	4	3	6
	50	19	9.5	199.8	138	391	2.0	1.3	0.000	2.6	6395.	4499.	21.8	1.2	8.0	7.1	10.1
X2	80	15	84	1	63	4.8	4	47	309	53	77	07	46	5	25	1	04
	47	19	9.8	202.3	144	378		1.3	0.000	2.3	6713.	4142.	20.1	1.2	7.4	6.5	10.6
X3	33	86	16	2	30	1.8	1.9	2	32	83	95	51	03	3	76	4	06
	54	19	15.	125.4	143	522	2.6	1.4	0.000	2.7	9161.	4831.	17.5	1.9	7.9	7.1	13.5
X4	00	80	79	4	82	3.9	4	09	299	27	36	51	78	2	96	5	65
	38	15	13.		113	361	2.2	1.3	0.000	2.4	6819.	3265.	17.4	2.0	8.4	7.1	14.8
X5	60	98	52	118.2	61	1.6	6	41	355	16	99	33	99	3	14	2	67
	54	18	20.		134	302	1.6	1.1	0.000	2.9	1021	4841.	16.3	2.5	8.5	7.6	16.0
X6	10	62	24	92.01	42	7.4	3	02	299	05	3.1	96	23	7	1	2	66
	63	24	18.	128.2	179	250	1.0	1.0	0.000	2.6	1239	5848.	15.6	1.8	7.0		13.7
X7	60	26	91	6	83	6.3	3	88	275	22	3.6	09	77	8	67	6.5	71
	39	14	9.0	161.5	102	279	1.9	1.2	0.000	2.7	4798.	3358.	22.9	1.5	9.3	7.9	11.3
X8	54	56	12	6	55	9.7	2	62	351	16	96	31	37	2	44	4	4
	41	14	8.5	166.4	996	230	1.6	1.1	0.000	2.9	4520.	3551.	24.7	1.4	9.8		10.6
X9	48	19	25	5	9	3.7	2	91	343	23	25	38	4	8	13	8.4	94
	31	86	12.	67.95	574	236	2.7	1.1	0.000	3.6	3738.	2533.	23.8	3.4	14.	11.	16.9
X10	06	0	66	2	7	7.2	5	91	397	12	39	84	11	1	07	5	3
	52	19	14.	133.7	141	258	1.3	1.3	0.000	2.6	8554.	4623.	18.0	1.8	7.9		13.1
X11	00	47	56	4	18	1.5	3	45	305	71	54	34	13	1	83	7.1	34
	22	88	7.9	110.9	589	118	1.3	1.0	0.000	2.5	2804.	1768.	23.8	2.1	11.	9.1	14.5
X12	82	0	33	3	4	6.2	5	01	466	93	03	21	01	6	83	7	39
	33	12	8.8	146.4	898	138	1.0	1.1	0.000	2.5	4243.	2745.	22.4	1.6	9.6		12.3
X13	27	91	14	7	5	7	7	38	384	77	93	46	25	7	89	8	59
	35	10	10.	99.27	719	169	1.6	1.1	0.000	3.3	4003.	2974.	24.6	2.3	12.	10.	13.7
X14	63	55	63	5	5	3.3	1	94	37	77	85	05	54	9	26	2	75
	42	18	18.	100.5	134	206	1.1	1.0	0.000	2.2	9664.	3625.	14.4	2.3	7.5	6.4	17.2
X15	22	66	56	5	74	6.7	1	49	339	63	31	43	01	6	27	6	3
	20	72	13.	53.86	477	127	1.7	1.2	0.000	2.8	3345.	1601.	19.9	4.2	13.	10.	21.9
X16	96	6	48	6	0	5.8	6	06	486	87	92	19	64	1	76	5	66
	29	85	12.	70.04	568	901.	1.0	1.0	0.000	3.4	3611.	2404.	23.6	3.3	13.	11.	16.8
X17	70	2	16	3	8	45	6	51	407	86	32	84	99	1	89	2	92
	24	84	28.	29.81	565	945.	1.1	1.0	0.000	2.9	6299.	1932.	14.0	7.2	12.		32.6
X18	62	8	45	1	9	02	1	97	448	03	85	03	63	9	74	10	01
	20	59	19.	31.23	385	114	1.9	1.0	0.000	3.4	3542.	1564.	19.0	6.9	16.	12.	28.5
X19	55	8	15	5	3	3.6	1	65	491	36	48	7	52	8	55	6	23
	19	77	19.	40.43	510	119	1.5	1.2	0.000	2.5	4450.	1462.	15.4		12.		28.5
X20	39	2	09	2	3	5.9	5	68	506	12	08	12	3	5.5	46	9.4	95
	12	58	27.	21.66	377	918.	1.5	1.2	0.000	2.1	4381.	908.7	12.0	9.7	13.	9.4	45.6
X21	90	7	1	4	6	93	7	53	624	98	39	36	29	9	44	7	45
	81	35	18.	19.65	219	621.	1.7	1.1	0.000	2.2	2159.	529.4	14.9	10.	17.	11.	46.7
X22	2	8	21	8	2	84	4	16	791	68	91	58	15	72	59	5	95
	93	36	30.	12.08	223	610.	1.6	1.0	0.000	2.5	3055.	621.8	12.7	16.	18.	12.	60.6
X23	2	4	12	5	2	93	8	56	737	6	95	53	55	6	5	3	68
	17	60	13.	44.47	390	719.	1.1	1.1	0.000	2.9	2857.	1310.	20.0	5.0	15.	11.	24.5
X24	65	5	6	2	3	92	9	56	531	17	06	18	7	3	19	3	85
	13	46	21.	21.53	291	904.	1.9	1.3	0.000	2.8	3047.	944.4	16.0	9.8	17.	12.	39.4
X25	33	4	55	5	5	26	5	59	614	73	95	31	61	5	28	2	96

Note: ω Q_b is bankfull stream power, and ω Q_{max} is stream power of maximum discharge.

The major limitation of these equations is that the established relations are empirical; the theoretical and semi-theoretical relations have not been sufficiently tested. In spite of that, those equations have good potential to extract newfangled information which can be utilized in the flood risk management. So employing those equations the total analysis is subdivided into six parts – measurement and estimation of (1) channel dimensions, (2) channel slope, (3) sinuosity, (4) mean flow velocity, (5) bankfull discharges and (6) stream power and shear stress.

4.1.1 Channel dimensions

The main channel dimensions include bankfull width, bankfull mean depth of channel, maximum depth of channel, bankfull cross-sectional area and channel width – depth ratio etc., which are widely used in the study of flood geomorphology, flood hydrology and palaeofloods (Williams, 1988).

4.1.1.1 Bankfull width (W_b)

Bankfull stage is the critical stage of a particular section of the stream at which that stream first overflows its natural banks (Langbein and Igeri, 1960). The analysis suggests that the river can be dived into two ideal segments – (1) mean W_b of 1603 m (Rhondia to Hatsimul) and (2) mean W_b of 617 m (Barsul to Paikpara). Due to obstacle of Anderson Weir (Rhondia) the river debouches its flood sediments annually behind and in front of weir, forming large size dunes on the bed. The highest sample W_b (1986 m) is observed at the cross-profile X3 (near Ramgopalpur) and lowest W_b (364 m) at profile X23 (near Jamalpur). With downstream increase of channel slope (provide energy to vertical incision) the narrowness of river is aggravated, reflecting negative correlation (-0.781) and slope dependency of W_b. Based on Pearson product moment correlation (significant in *t*-test) and non-liner regression (high percentage of relationship explanation) it is cleared that annual maximum discharge ($Q_{max} = 2154\ e^{0.001Wb}$), shear stress of bed and banks ($\tau = 436.8\ W_b^{-0.52}$) and importantly stream power (ω) of bankfull discharge ($\omega\ Q_b = 113.9\ W_b^{-0.36}$) and annual maximum discharge ($\omega\ Q_{max} = 4925\ W_b^{-0.8}$) are highly correlated and dependent on W_b of channel segments.

4.1.1.2. Maximum depth (D_{max})

Maximum depth, D_{max} , is the elevation difference between lowest bank-top and thalweg at a cross-section of the river (Wolman and Leopold 1957; Williams, 1988). It has been noticed that the upper segments of Damodar river with high W_b are associated with low D_{max} (8 – 15 m) but after crossing Barddhaman town is getting high value up to Paikpara (12 – 30 m) following the tight valley alignment. In the downstream of Palla (X 19), sudden increase of channel depth and also channel slope can be result of neo-tectonic and topographic control over the reach. The reason behind this is undeniable as a north to south Damodar Fault (Singh et al., 1998) existed below this area, directing the southern shift of Damodar and fan-deltaic sedimentation. The lowest D_{max} (7.93 m) is found at X 12 profile (near Edilpur) with high fluvial aggradation and highest D_{max} (30.12 m) at X 23 profile (near Jamalpur) with sinuous thalweg and vertical cliff.

4.1.1.3. Bankfull cross-sectional area (A_b)

It is the maximum area of active channel along which the maximum volume of water passing through, irrespective of channel roughness and bend geometry. Based on A_b data the study area can be divided into two broad segments – (1) high and variable A_b (3500 – 6000 m^2) from Rhondia to Hatsimul, and (2) low and least variable A_b (800 – 2100 m^2) from Barsul to Paikpara. The first segment category is associated with broad valley, well-developed floodplain and lateral containment but second segment includes narrow valley, entrenched floodplain, elevated levee and vertical containment with sinuous thalweg. With increasing distance (D_T) from Rhondia the A_b is gradually declined ($A_b = 2425.6\ e^{-0.0194\ D_T}$). The wide A_b has shape of wide box with undulation of river bed due to in channel bars but low A_b has almost trapezoidal shape. Again there is a strong positive correlation (0.843) in between A_b and Q_{max} which denotes the exponential growth ($Q_{max} = 2099\ e^{0.001\ A_b}$) of annual maximum discharge as A_b is increased in the channel segments (table 3). Applying the equations 6 and 7, we have got exaggerated result on A_b in respect of actual A_b. The channel belt (B) is potentially decreased as the A_b and W_b reduced downstream (figure 6).

4.1.1.4. Channel width – depth ratio (W_b/D_{max})

The width – depth ratio (W_b/D_{max}) is the important quotient of W_b and D_{max} of a particular channel cross-section which describes the shape factor of the reach (Rosgen, 1994). Wolman (1955), Gregory and Walling (1973), Pickup and Warner (1976) and Williams (1978) suggested that the minimum width – depth ratio (W_b/D_{max}) of the cross-section has the advantage of being a consistent and objective way to define bankfull. As the downstream distance (x axis) increased from Rhondia, the W_b/D_{max} (y axis) of reaches is declined significantly, carrying a linear growth function of distance (R^2 = 0.753). Up to Hatsimul (X 15 profile) W_b/D_{max} varies from 67 to 202 signifying high amount of potential bankfull discharge, low competence to transport coarse sediments (high degree of braiding) and high expansion of active channel belt. From Barsul (X 16) to Paikpara (X 25) the W_b/D_{max} is declined abruptly from 53.86 to 21.53, signifying narrowness of channel, low limit of bankfull discharge (i.e. high flood risk as threshold level), relatively high competence to transport sediments in floods and increase boundary shear stress (i.e. high chance of bank shifts). The flood-prone width (F_p), channel belt (B), mean annual bankfull discharge with 2 years recurrence interval (Q_{max2}) and volume of channel segment (V_p) are significantly related and dependent on W_b/D_{max} in the sample segments of Damodar river, showing geometrical progress function of W_b/D_{max}.

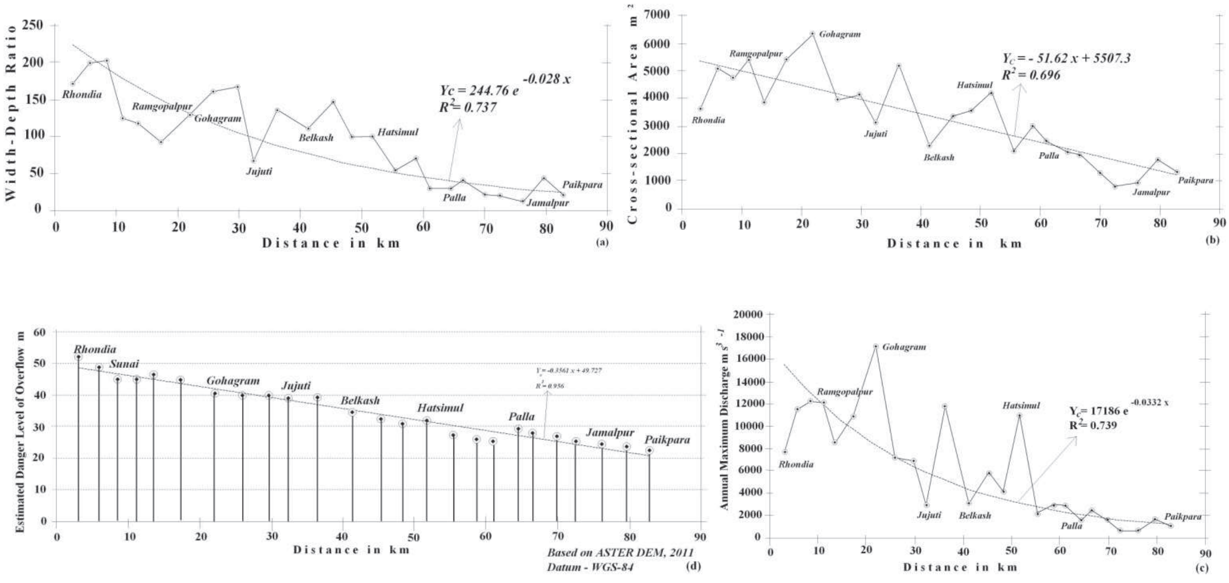

Figure 6: With increasing downstream distance from Rhondia (a) W_b/D_{max} is decreased, (b) A_b is decreased, (c) limit of Q_{max} is decreased and (d) estimated gauge heights (G_H) are gradually reduced

4.1.1.5. Entrenchment ratio (ER)

Entrenchment ratio (ER) is the ratio of the width of the flood-prone width (F_p) (near to channel belt) and to the bankfull width of the channel. According to Rosgen (1994) entrenchment ratio of 1 – 1.4 represent entrenched streams, 1.41 – 2.2 represent moderately entrenched streams and ratio greater than 2.2 denote slightly entrenched streams (i.e. well-developed floodplain). From Rhondia (X 1) to Jujuti (X 10) the average ER of 2.09 reflects moderately to slightly entrenched channel because of high flood-prone width in respect of bankfull width. The floodplain of this region is coupled with wide palaeochannels, mature points bars (locally named as mana) and broad alluvial terraces. From Belkash (X 11) to Barsul (X 18) the average ER suddenly drops to 1.29, signifying a well entrenched channel where F_p and W_b are not deviated very much in respect each other. Again from Palla (X 19) to Paikpara (X 25) the average ER is raised to 1.65, carrying evidence of moderate entrenchment. It is noticed that 52 percent of channel segments can be regarded as moderately entrenched channel.

4.1.1.6. Gauge height (G_H)

Flood is a body of water which rises to overflow the land which is not normally submerged (Ward, 1978). In India, in the common parlance, a river is said to be in flood when its water level crosses the Danger Level (DL) at the particular site and when a flood crosses the DL by 1 metre or more, it is termed as major flood at that site (Dhar and Nandargi, 2003). More simply, the bankfull stage (i.e. gauge height, G_H) can be determined just from the floodplain profile, where this profile intersects the gauge, if a local bench mark is available for the relating the profile to G_H (Williams, 1976). Lower segment of Damodar river Basin has six gauge stations at Rhondia (Extreme Danger Level, EDL – 53.490 m), Edilpur (EDL – 32.940 m), Jamalpur (EDL – 23.530 m), Amta (EDL – 6.240 m), Champadanga (EDL – 13.490 m) and Harinkola (EDL – 12.80 m) respectively, under the control of IWD. In the study area there are only three gauge stations (Rhondia, Edilpur and Jamalpur) but taking into account 25 cross-sections (figure 2) we have tried to estimate the true bankfull stage at each section using ASTER DEM. Using WGS-84 datum surface of ASTER DEM we have calculated the critical height of flood flow at those sections to define the threshold limit of bankfull discharge for a given A_b, W_b and D_{max}. The critical bankfull limits of flood flow (i.e. extreme G_H from mean sea level) are 45.017 m at X 3 (near Kasba), 46.172 m at X 5(near Gohagram), 40.015 m at X 8 (near Majher Char), 34.567 m at x 12 (near Belkash), 31.676 at X 15 (near Hatsimul), 28.762 m at X 19 (near Palla), 24.453 m at X 23 (near Jamalpur) and 22.235 m at X 25 (Paikpara) (figure 6d).

4.1.2. Channel slope (S)

The channel slope (S; metre/metre or degree) can be determined by the elevation difference of thalweg at two successive points and the common distance between two points. The value of slope (S) is increased gradually as the W_b/D_{max} and Q_b are declined towards Paikpara, signifying the topographic control on valley alignment. The slope varies from 0.00036 ^{o} to 0.00079^o signifying the low channel competence to heavy load in flood stage. For that reason the high degree of braiding and aggradations is observed in between Durgapur and Belkash. From the analysis we have found that the parameter of channel slope (developed by Leopold and Wolman, 1957) is driven the major variables of channels, viz., B, Si (i.e. sinuosity index), V_p, Q_{max}, Q_b, ω Q_b and ω Q_{max} respectively. On the other hand W_b, W_b/D_{max} and M significantly influence the degree of channel slope (table 2). For example, as the percentage of fine materials (silt and clay) of bed and banks are increased downstream the slope of channel is increased to accommodate sediment laden flood water within the entrenched and narrow valley. Because with increasing downstream channel distance the W_b/D_{max} is radically reduced and hydraulic sinuosity index (after Mueller, 1968) of confined valley (i.e. high levee and embankments) is amplified than upstream section. Though, the slope would be controlled by Damodar Fault which can be acted as extrinsic threshold to the fluvial system.

Table 2: Dependency and independency of channel slope up on percentage of fine materials, bankfull width, width-depth ratio, channel belt, sinuosity index, bankfull discharge, annual maximum discharge, segment volume, stream power of Q_b and Q_{max} in the Damodar river

X	Y	Established Regression	Correlation Coefficient (*r*)
M	S	$S = 0.0003\ M^{0.3408}$ $R^2 = 0.798$ SE = 0.0003 log unit	0.907
W_b		$S = 0.0132\ W_b^{-0.4979}$ $R^2 = 0.943$ SE = 0.0002 log unit	-0.865
W_b/D_{max}		$S = 0.0016\ W_b/D_{max}^{-0.3156}$ $R^2 = 0.798$ SE = 1.58 log unit	-0.78
S	B	$B = 0.0006\ S^{-2.084}$ $R^2 = 0.943$ SE = 3.39 log unit	-0.856
	Si	$Si = 1379\ S + 0.904$ $R^2 = 0.656$ SE = 3.304 log unit	0.834
	Q_b	$Q_b = 0.022\ S^{-1.48}$ $R^2 = 0.957$ SE = 2.824 log unit	-0.898
	Q_{max}	$Q_{max} = 0.2191\ S^{-1.28}$ $R^2 = 0.658$ SE = 3.304 log unit	-0.682
	V_p	$V_p = 9.165\ S^{-1.78}$ $R^2 = 0.763$ SE = 0.0002 log unit	-0.865
	$\omega\ Q_b$	$\omega\ Q_b = 1131\ S^{0.621}$ $R^2 = 0641$ SE = 0.136 log unit	0.756
	$\omega\ Q_{max}$	$\omega\ Q_{max} = 4.23\ e^{3.42\ S}$ $R^2 = 0.817$ SE = 0.734 log unit	0.916

Note: (1) $W_b/D_{max} = 255\ M^{-1.08}$, developed by Schumm (1963); transformed this equation into log form with base 10 to find out M, the final equation is appeared as: $-1.08 \log_{10} M = \log_{10} W_b/D_{max} - 2.406$; (2) In all cases calculated t is more than the tabulated t at 95% and 99% level of significance (two-tailed); so null hypothesis is rejected. There are significant relationships among

4.1.3. Sinuosity (Si)

Channel sinuosity (Si) of a wide river is estimated as the ratio between channel thalweg length (L_T) and shortest distance between two cross-sections (L_D) using the satellite images and GIS (Friend and Sinha, 1993; Rosgen, 1994; Sinha and Friend, 1994). The average sinuosity index of Damodar is 1.19 which signifies the almost straight river course with the topographic confinement and fault-guidance. Except upper segments (X 2, 3, 4 and 5) and lower segments (X 20, 21 and 25) all other segments of Damodar are associated with less than Si of 1.20. Topographic Sinuosity Index (after Mueller, 1968) of Damodar suggests that the contribution of topographic and tectonic control on the straightness of channel varies from 68 to 92 percent in between Rhondia and Paikpara (Ghosh and Mistri, 2012). Bridge (2003) have proved that sinuosity appears to increase with water and sediment discharge from straight to sinuous single channels (as observed in the study area), but then decreases towards the transition to braiding. Thus, sinuosity is generally not inversely related to channel width-depth ratio nor to the percentage of silt and clay on the bed and banks as suggested by Schumm (1963).

4.1.4. Flow velocity (V_C)

The applied equations 26 and 27 provide more or less same result but it is found that the downstream flow velocity of flood is increased as the D_{max} and S increased (applying equation 28). Up to Barsul the potential V_C varies from 14 to 25 m s^{-1} whereas up to Paikpara it varies from 12 to 22 m s^{-1}. The hydraulic radius of Damodar ranges in between 2.2 to 3.4 m. The sections with high hydraulic radius (> 2.8 m) and high wetted perimeter are associated with relatively high velocity in respect of average *n* (i.e. 0.045 for sandy bed) in this river.

4.1.5. Bankfull volume (V_P) and discharge (Q_b)

The bankfull discharge at a river cross-section is the flow which just fills the channel to the tops of the banks and such a discharge therefore marks the condition of incipient flooding (Williams, 1978). According to Rosgen (1994) bankfull discharge is defined as the momentary maximum peak flow; one which occurs several days in a year and is often related to the 1.5 years recurrence interval discharge. The potential volume of each segment and bankfull discharges are calculated using the following methods.

4.1.5.1. Volume (V_P)

For computation of the volume of a reach, the sectional areas of the cross-sections are estimated using the method of cut and fill volumes in GIS. In between two sections the potential volume of segment (V_P) is calculated using the trapezoidal rule (average end area rule) (Basak, 1994):

Potential Average Volume (V_P) =

$$(D/2)\,[A_1 + A_n + 2\,\Sigma A_{n-1}] \qquad (1)$$

where D is the common distance, A_1 is the area of 1st cross-section, A_n is the area of the last cross-section and is ΣA_{n-1} the summation of other sections.

Up to Barsul (X 15) the average potential V_P is 1, 47, 31, 000 m^3, whereas up to Paikpara it reduces to only 59, 00, 400 m^3. With increasing channel distance from Rhondia the carrying capacity to accommodate water in an instantaneous time is gradually declined as the cross-sectional area is reduced. It is understood that except channel storage the given volume of huge flood water which passes through upstream bankfull sections, is not easily accommodate in the downstream sections. Therefore, there is ample chance of overflow and bank erosion at time of monsoon peak discharge below Jamalpur and Paikpara.

4.1.5.2. Bankfull discharge (Q_b)

It is the maximum amount of water which is carried by a specific channel before the overflows and floods (Williams, 1988). Rotnicki (1983) and Pickup and Warner (1982) developed an equation to estimate bankfull discharge (Q_b) relating with the cross-sectional area (Kale et al., 2004). Q_b is the safe discharge in respect of A_b, which annually observed for a few days in the monsoon depression. Applying the equations of 35 and 36, in the time of peak monsoon the maximum Q_b can be observed at X 7 section (near Gohagram) with discharge of 4210 m^3 s^{-1} and 5848 m^3 s^{-1} respectively. The analysis of bankfull discharge (i.e. annually observed in the active floodplain) suggests that Damodar river can be classified into three important segments – (1) channel segment of Rhondia to Masjidpur (X1 to X 11) with Q_b of 3312 to 4048 m^3 s^{-1}, (2) channel segment of Belkash to Palla (X 12 to X 19) with Q_b of 2327 to 2428 m^3 s^{-1}, and (3) channel segment of Habaspur to Paikpara (X 20 to X 25) with Q_b of 963 to 1274 m^3 s^{-1}.

4.1.5.3. Annual maximum or peak discharge (Q_{max})

Applying the equations 19, 20 and 21, we have found that up to X 15 profile the maximum monsoon discharge varies greatly from 4,130 to 17,190 m^3 s^{-1}, with mean of 8,852 m^3 s^{-1}. After crossing Barsul, up to X 25 profile, the Q_{max} is reduced from 2,870 to 1,066 m^3 s^{-1}, with mean of 1,736 m^3 s^{-1}. Again applying equation, the mean Q_{max} of X 1 – X 15 ranges from 6,232 to 6,462 m^3 s^{-1}, whereas the mean Q_{max} of downstream sections varies from 2,923 to 3,675 m^3 s^{-1} (figure 7).

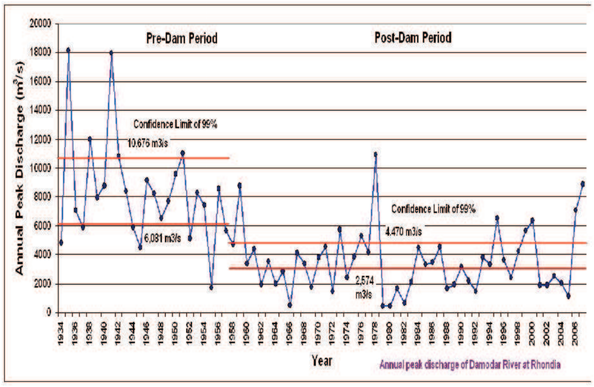

Figure 7: Pre-dam and post-dam spectrum of annual peak discharge in the Damodar river, recorded at Rhondia (data source: Bhattacharyya, 2011)

This analysis directly reflects two facts – (1) downstream reduction of bankfull width, cross-sectional area and width-depth ratio (i.e. channel dimensions) decline the limit of annual maximum discharge which can be safely accommodated by the channel, and (2) uncertainty of monsoon rainfall and tropical cyclones can create huge pressure on the river engineering structures because of lowering safe limit to release excess water through the narrow and heavily silted lower Damodar.

4.1.6. Stream power (ω) and shear stress (τ)

Several studies (Baker and Coasta, 1987; Kochel, 1988; Rajaguru et al., 1995; Kale et al., 1996; Kale, 2003) have shown that the flood magnitude is not as important with regard to geomorphic work as the flood power in the monsoon episode. Calculations indicate that average estimated stream power of Q_b varies from 6 to 8 W m^{-2} in between Rhondia and Hatsimul (X 1 to X 15 profiles) but it increases greatly from 9 to 12 W m^{-2}. Up to X 15 profile the average stream power of Q_{max} varies from 10 to 16 W m^{-2}, but again it suddenly rises from 20 to 60 W m^{-2}. On an average the Damodar river is able to carry huge amount of sands (critical limit 1.02 W m^{-2}) and pebbles (critical limit 1.5 to 16 W m^{-2}) annually. For that reason the upstream sections of study area are largely associated with aggradational landforms and braiding pattern (i.e. siltation of beds and reservoirs) than downstream. Therefore, it is very easy to assume about the annual bulk of coarse sediments, transported downstream by Damodar at the time of floods. For that reason the siltation rates of Maithon and Panchet reservoirs are 1310.0 and 1049.0 m^3 km^{-2} $year^{-1}$ respectively (Lal et al., 1977) and 39 percent of storage capacity is already lost in Durgapur Barrage (Rudra, 2010). In respect of high hydraulic radius and moderate slope and shear stress of upstream sections (X 1 to X 15 profiles) varies slightly from 7 to 10 N m^{-2}, but with increasing downstream channel distance it raises from 13 to 17 N m^{-2}, signifying high stress on bed and banks (i.e. risk of bank failure and avulsion). The flood generating shear stress of 10 N m^{-2} can entrain and transport sediments of about 1 cm distance and can carry sediments finer than 1 mm in suspension (Kale, 2003). From Barsul the low width-depth ratio, low W_b, relatively high channel slope, high hydraulic radius or high mean depth of channel determine the high shear stress and hydraulic power in the time of most of the large floods. Alongside the shear stress on bed and banks of Damodar is the geometrical progression function of Q_b ($\tau = 0.5959\ \omega Q_b^{1.3358}$) and Q_{max} ($\tau = 2.7854\ \omega Q_{max}^{0.4701}$) stream power with high value of r and R^2 (figure 8).

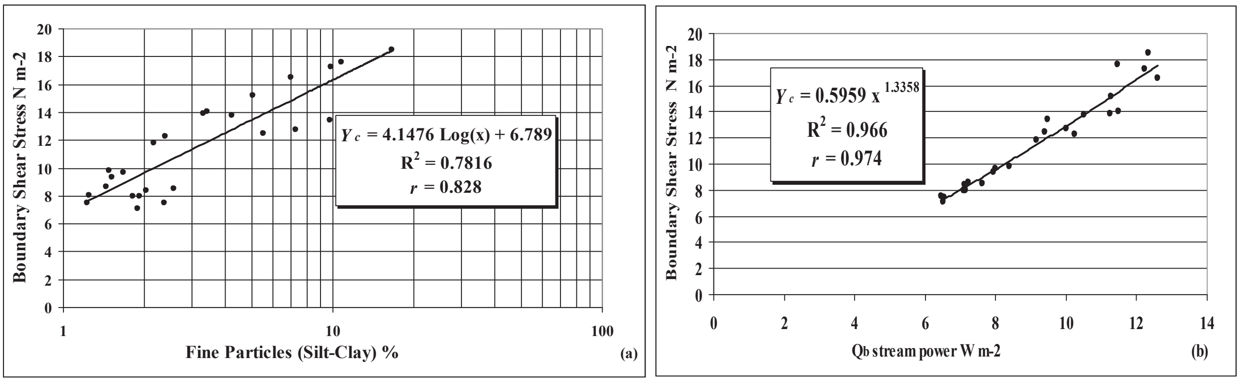

Figure 8: Boundary shear stress (τ) is significantly increased with (a) increasing percentage of silt and clay (M) at downstream segments, and (b) increasing bankfull stream power (ω Q_b)

4.2. Relative dominance of variables and clustering

It has been found that the geomorphic and hydrologic variables do not operate in isolation. Rather they are closely interlinked with each other and drive the fluvial system towards dynamic meta-stable equilibrium. So a multivariate analysis seems to be quite necessary to recognize the relative importance and dominance of each variable in respect of total system (Ghosh, 2011). In factor analysis (a technique of multivariate analysis) of hydrogeomorphic phenomena, often volumes of data having many variables are analyzed. It is one of fundamental techniques to find out the interdependent variables or latent which creates the commonality (Kothari, 2009; Ghosh and Bhattacharya, 2012). So to reduce the number aforesaid variables or channel dimensions into few factors or components the Principal Component Analysis (PCA) is employed. In the present study, there are 17 variables of 25 sample sections. The importance of principal components (PC) is expressed as eigen values which signifies the most effective components with increasing numbers of dominant variables and their role in the system functioning. Three principal components, cumulatively explaining 88.13 percent of total variance and having three eigen values of 10.42 (PC 1), 2.86 (PC 2) and 1.69 (PC 3) respectively (table 3), were considered.

High eigen value (10.42) of PC 1 signifies the maximum dominance of factors (i.e. A_b, W_b, W_b/D_{max}, B, F_P, Q_{max}, Q_b, S, M, τ, ω of Q_b and Q_{max}) in the fluvial system of Damodar river with maximum degree of interplay. The next eigen values of PC 2 (2.86) and PC 3 (1.69) show low dominance of factors in the system. So principally the reaches of Damodar are mainly controlled or influenced by the dominant variables of PC 1 than PC 2 and PC 3.

- **PC 1:** Mainly bankfull area (A_b), bankfull width (W_b), width-depth ratio (W_b/D_{max}), channel belt (B), flood-prone width (F_P), annual maximum discharge (Q_{max}) and bankfull discharge (Q_b) drive the fluvial system of lower Damodar positively, whereas channel slope (S), percentage of silt-clay on bed and banks (M), shear stress, stream power of Q_b and Q_{max} influence same system in a negative direction (61.33 % of total variance).
- **PC 2:** Mainly Q_{max} and maximum channel depth (D_{max}) have high positive dominance where hydraulic radius (R) and maximum flood velocity (V_C) stoutly influence the system in a negative direction (16.81 % of total variance).
- **PC 3:** Principally channel planform dimensions (i.e. sinuosity index, Si and entrenchment ratio, ER) are getting highly positive importance (9.97 % of total variance).

Table 3: Extraction of three principal components of selected variables of sections and their relative dominance

	A_b	Wb	D_{max}	W_b/D_{max}	B	F_p	ER	Si	S	R	Q_{max}	Q_b	V	M	τ	ω Q_b	ω Q_{max}
PC 1	**0.95**	**0.96**	-0.57	**0.89**	**0.95**	**0.83**	0.17	0.336	**-0.94**	-0.12	**0.73**	**0.95**	0.35	**-0.88**	**-0.96**	**-0.9**	**-0.88**
PC 2	0.123	0.254	**0.728**	-0.2	0.27	0.04	-.22	0.065	0.136	**-0.64**	**0.59**	0.149	**-0.9**	0.36	-0.17	-0.32	0.42
PC 3	-0.13	-0.06	-0.07	0.12	-0.06	0.47	**0.84**	**0.7**	0.183	-0.30	-0.22	-0.13	-0.07	0.131	0.037	-0.04	0.14

The transformation of component values to component prinsscores (i.e. putting the value on space) we have found the reflection of each channel section based in the interplay of aforesaid variables. The formula of finding each prinsscore in the first principal component loading cab be defined as

$$\text{Prinsscore of profile X1} = \sum [V_i \text{ PC1} / \alpha_{PC1}^{0.5}] \quad (2)$$

where, V_i are the actual values of variables (i = 1, 2, 3…..n) in section X1, PC1 are the component value of variables and α_{PC1} is the eigen value of PC1. Calculating the prinsscores of PC1 and PC2 we have employed Z-score to standardize the data and plotted the result in x,y coordinates to find out the clustering. The main purpose of this discriminant analysis is to cluster the groups of channel segments which are discriminated from other groups and it tries to recognize the maximum likelihood behavoiur of hydrogeomorphic variables on sample sections. Two separate classes of segments are categorized based on the cluster analysis (figure 9):

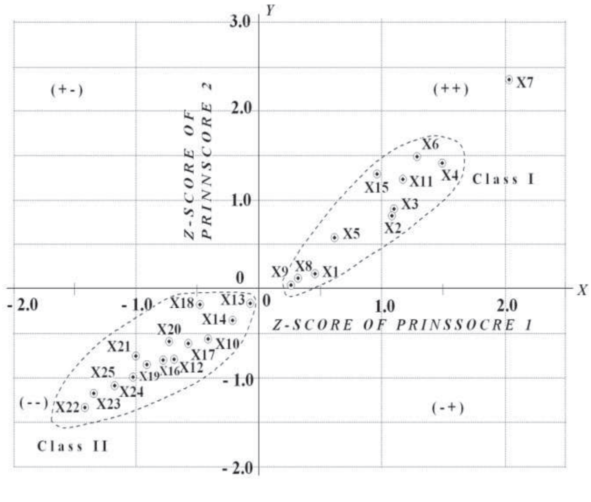

Figure 9: Clustering of channel cross-sections to define class I and class II categories of channel morphology using the Z-scores of PC 1 and PC 2 prinsscores in the Damodar River

- **Class I (Tending to Braiding and Lateral Expansion) –** Upstream sections of Damodar river (X 1 to 6, X 8, X 9, X 11, X 15 including X 7) are showing positive z-scores based on the mutual interactions of channel dimensions and hydraulic parameters. The individuality or distinctiveness of this fluvial class is mainly associated with high A_b (3500 – 5500 m^2), high W_b (1400 – 2400 m), low D_{max} (8 – 15 m), high W_b/D_{max} (120 – 200), high B (> 12,000 m), low ER (> 1.4), low Si (< 1.25), low S (< 0.0004^0), high limit of Q_{max} (4500 – 9000 m^3s^{-1}) and Q_b (3000 – 5000 m^3s^{-1}), low τ (< 9.5 N m^{-2}) and high ω of Q_{max} (10 – 13 W m^{-2}).
- **Class II (Tending to Meandering and Lateral Confinement) –** Downstream sections of Damodar river (X10, X 12 to 14, and X 16 to X 25) are getting individuality based on the following variables – low A_b (900 – 3000 m^2), low W_b (500 – 1200 m), high D_{max} (16 – 25 m), low W_b/D_{max} (20 – 100), low B (< 1,500 m), high ER (1.0 – 1.4), moderate Si (1.25 – 1.45), moderate S (0.0004^0 – 0.0007^0), low limit of Q_{max} (2200 – 4400 m^3s^{-1}) and Q_b (1000 – 3000 m^3s^{-1}), low τ (10 – 15 N m^{-2}) and high ω of Q_{max} (> 15 W m^{-2}).

5. Conclusions

From the above analysis it is now understood that river forms and fluvial processes evolved simultaneously and operated through mutual adjustments toward self-stabilization in different reaches of Damodar. Categorization of channel segments predicts the river's behaviour to internal and external factors and it explains the current stage of morphological stability to affect channel discharge, aggradation and degradation. The study brings out following important findings –

- At upper segment there is a tendency of avulsion, multi-channel river bed and in-channel aggradation (i.e. formation of bars and islands) due to loss of kinetic energy and competence of stream in the time of floods. Downstream segments indicate narrow sinuous channel (single thalweg) with pool-riffle sequence, river tightness and development of point bars.
- In the upper reach as the width of flood-prone area is increased the entrenchment of channel is gradually decreased, i.e. more aggradational landforms in the active channel belt, but in the lower reach opposite situation is found.
- The slope of channel directly controls the variables of B, Si, Q_b, Q_{max}, V_p, ω Q_b and ω Q_{max} in the study area. The slope in turn is controlled by the basement faults and lineaments.
- The Damodar river (i.e. area under study) can be categorized into two broad patterns – (1) the bed-load channel from Rhondia to Barddhaman and (2) the mixed-load straight channel from Barddhaman to Paikpara.

- PCA suggests that present stream pattern morphology of Damodar is directly influenced by eight major variables namely channel width, depth, flow velocity, peak discharges, channel slope, sediment load and boundary shear stress.
- On the basis of textural pattern of active floodplains, specific stream power, landforms, channel planform, aggradation and degradation the Damodar floodplain can be genetically categorized into two parts – (1) medium energy (10 – 20 W m^{-2}) non-cohesive floodplains from Barsul to Paikpara and (2) low energy (< 10 W m^{-2}) non-cohesive floodplains from Rhondia to Hatsimul.
- Different segments of Damodar river can be categorized on the basis of two broad levels, namely the geomorphic characterization (level I) and the morphological description (level II).

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