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CASE STUDY

Hydrogeomorphic variability due to dam constructions and emerging problems: a case study of Damodar River, West Bengal, India

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Abstract In the first multipurpose river valley planning of India, the vast resources of Damodar River Basin (DRB) (eastern India) are not only to be envisioned in their entirety but also to be developed in a unified manner where the water, land, and people are simultaneously bounded in a seamless web. Four large dams (Konar, Tilaiya, Maithon, and Panchet), Durgapur barrage, and Tenughat reservoir are built to tamp the flood-prone Damodar River using water resource in an integrated method. The functionality of Damodar fluvial system is controlled by dams, barrage, weirs, sluices, embankments, and canals, maintaining a dynamic equilibrium between fluvial processes and anthropogenic processes. Carrying more than 50 years of legacy, the existing drainage and flood control system of Damodar Valley Corporation has aggravated a number of hydrogeomorphic problems especially in lower DRB, viz. siltation of river bed and reservoirs, uncontrolled monsoonal stream flow, declining carrying capacity of lower course, drainage congestion, low-magnitude annual floods, channel shifting, de-functioned canals, decay of paleo-channels, decline of ground water level, and less replenishing of soils with fresh silts. The present paper is mainly tried to investigate the pre-dam and post-dam hydrogeomorphic variability in relation to flood risk and drawbacks of Damodar Valley Multipurpose Project. Specifically, the annual peak flow of Damodar shifts from August to September due to dam construction and reservoir storage. Applying the annual flood series of log Pearson type III distribution, we have estimated post-dam 5-year peak discharge of above 5,300 $m^3 s^{-1}$ and 100-year flood of above 11,000 $m^3 s^{-1}$. Due to siltation, the bankfull discharges of sample segments are gradually declined up to 4,011 $m^3 s^{-1}$, 2,366 $m^3 s^{-1}$,

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and 1,542 $m^3\ s^{-1}$, respectively, having recurrence interval of 1.18–3.18 years only. With the regulation of monsoon flow, the standard sinuosity index is gradually increased downstream, having high dominance of hydraulic factors in respect of topographic factors. The upstream section of study area (Rhondia to Paikpara) now shows the dominance of aggradational landforms, braiding, avulsion, high width–depth ratio, breaching of right bank, and valley widening, but downstream of Barsul the phenomena of bank erosion, confined sinuosity, low width–depth ratio, and narrowness are more pronounced.

Keywords Dam · Hydrogeomorphology · Flood · Paleochannels · DVC · DRB

1 Introduction

Large dams and development are interrelated, and this acquaintance may be implemented in an integrated way to boost up the economy of backward region using mainly the water, mineral, and power resources. Development has been defined as a dynamic process of growth, expansion, or realization of potential, bringing regional resources into full productive use (Husain 2011). Regional development emphasizes on re-organizing the space for its comprehensive development with a view to providing ideal living conditions to all human communities in all regions of human occupance not in isolation from each other but in integration with each other (Chandna 2008). In India, one of the earliest outcomes of comprehensive regional planning was enacted as the multipurpose river valley project, constructing large dams on major rivers (focusing on flood mitigation, irrigation and hydropower). Importantly, the first river valley project of India was jointly implemented in Damodar River Basin (DRB) by the states of Jharkhand (then Bihar) and West Bengal under the great leadership of first Prime Minster, Pandit Jawaharlal Nehru. The most significant geographical aspect of this developmental program is the modification of natural spatial unit, i.e., drainage basin, which is the fundamental unit of geomorphic and hydrological study. Under the Damodar Valley Multipurpose Project (DVMP), the vast resources (water, minerals, coals, forest, and alluvial soils) of DRB are not only to be envisioned in their entirety but also to be developed in an integrated way where the water, land, and people are simultaneously bounded in a seamless web (Krik 1950; Saha 1979). The large-scale modification of river basin is enacted by the fluvial engineering structures, including dams, barrages, weirs, sluices, canals, and embankments, to regulate stream flow and to use water resource in productive ways (Mishra 2001). However, river basins are considered an important repository of neo-tectonic, hydrological, climatic, and anthropogenic changes because the fluvial system is the most sensitive elements of the earth’s surface, and any shift in environmental conditions instigates a rapid response from the fluvial system (Sridhar 2008; Singhvi and Kale 2009). So the construction of dams and other structures on the river demolishes its previous natural entity and compels the fluvial system to enter into a new phase of equilibrium with changing aggradation and degradation processes.

Up to 1900, there were only 81 dams in India, while in 1950 and 2012, the number jumps into 302 and 4,818, respectively (Indian Central Water Commission 2012). As the dam construction has increased in India and other developed country, the number of publications on the effects of dam construction on physical and socio-economic environment around the world has also increased. The assessment of general effects of dams and response of fluvial system can be found in the writings of Morris and Fan (1997), Barrow (1987), and Xu (1990). The geomorphic downstream effects of dams have been studied by

Williams and Wolman (1984), Graf (2006), Brandt (2000a, b), Grant et al. (2003), Hupp et al. (2009), and Wildi (2010). The effects of Damodar Valley Project (DVP) on the river are precisely analyzed by Bhattacharya (1959), Chatterjee (1969), Bagchi (1977), Saha (1979), Sen (1985, 1991), Choudhury (1995), Chandra (2003), Lahiri-Dutt (2006), Rudra (2002, 2010), Mukhopadhyay and Dasgupta (2010), Ghosh (2011), and Bhattacharyya (2011). On the basis of reviews of the previous literatures and the empirical observations, the main aim of this study is to synthesize the new-fangled information and significant findings about the downstream hydrogeomorphic impacts and variations (in relation to flood risk) due to DVP. The objectives are set forth as follows:

1. To understand the impact of infrastructures on the floodplain of Damodar River,
2. To analyze the dam-induced geomorphic and hydrologic changes in the Damodar River, and
3. To estimate pre-dam and post-dam flood frequency including potential bankfull discharges.

2 Materials and methods

The study about fluvial dynamics, river morphology, and floods always incorporates an interdisciplinary approach of earth science, including modern methods and advanced techniques of hydrology, fluvial geomorphology, quaternary geology, remote sensing, and Geographic Information System (GIS). The study area includes the lower segment of Damodar River in between Rhondia (23°22′8″N, 87°28′25″E) and Paikpara (23°00′58″N, 87°57′41″E) having length of 82 km (Fig. 2). Downstream of Asansol, the river crosses the hindrances of Durgapur Barrage (at Durgapur) and Anderson Weir (at Rhondia), and then, it flows almost straight up to Barsul and Palla with a conspicuous bed toward south. Downstream of Paikpara, it subsequently bifurcates into two main distributaries, Damodar (left) and Mundeswari (Right). This segment of channel belt has lots of paleogeomorphic significance because the fault-guided course of lower Damodar (Singh et al. 1998) was previously shifted many times during extreme floods and left many paleochannels on Quaternary fan-deltaic sedimentary units of western Bengal Basin (Niyogi et al. 1970; Niyogi 1975; Acharyya and Shah 2007). Selecting this spatial unit and incorporating the secondary information, toposheets, satellite images, quantitative techniques, and GIS, an attempt is made here to employ the approach of "hydrogeomorphology" which is the earth science relating to the geographical, geological, and hydrological aspects of water bodies and changes to these in response to flow variations and to natural and human-caused events (Scheidegger 1973; Babar 2005). Hydrogeomorphology also includes the interplay in between ability of streamflow to transport sediments and incoming sediment flux (Grant et al. 2003). We have collected secondary data and information mostly from the writings of Chatterjee (1967) and Bhattacharyya (2011), official Web sites of Irrigation and Waterways Dept. of West Bengal (www.wbiwd.gov.in/), West Bengal State Marketing Board (www.wbagrimarketingboard.gov.in/), Indian Meteorological Department of India (www.imd.gov.in/), published reports of Geological Survey of India (Bhattacharya and Dhar 2005), Google Earth, SRTM (Shuttle Radar Topographic Mission) data (www.srtm.csi.cgiar.org/), and different research articles relating to Damodar River. We have also used the toposheet NF 45-C of the United States Army Corps of Engineers (USACE) (1922–43), toposheets (1969–74) of Survey of India (SOI) (73 M/7, M/11, M/12, M/15, M/16, N/13 and 79 A/4), Global Land Cover Facility (GLCF) (www.glcf.umd.edu/) satellite images of Landsat MSS

(1972–73), Landsat TM (1990 and 2006), and Landsat ETM + (2000). The methodology of this research is depicted in a flowchart (Fig. 1).

Taking all raster layers, we have reprojected the maps and images in UTM WGS-84 projection system in ArcGIS 9.3 and Erdas Imagine 9.1 software to minimize error in images mosaic and superimposition of layers. Observing the direction of valley, sudden change in plan-form, and bed topography, we have subdivided Damodar River into few segments for detailed analysis of geomorphic indexes. To get parametric values of sinuosity index (Mueller 1968), braiding index (Brice 1964), braid-channel ratio (BR) (Friend and Sinha 1993), and other quantitative index for geomorphic analysis, we have created vector layers on five geo-referenced images in MapInfo 11.0 software on by one, digitizing the river and both banks. To locate the sites of fluvial degradation and aggradation, we have superimposed the vector layers of channel in GIS to get comparable picture. The sectional profile of Damodar River is derived from the GPS survey (Garmin GPS 76CSx device, $+3<$ error <-3) with UTM Projection and WGS-84 datum, and the vulnerable locations of bank erosion are verified in the field using GPS locations. The employed techniques are summarized as follows.

The sinuosity index of Mueller (1968) can be written as

$$\text{HSI (Hydraulic Sinuosity Index)} = \%\text{ equivalent of } (\text{CI}-\text{VI})/(\text{CI}-1) \tag{1}$$

$$\text{TSI (Topographic Sinuosity Index)} = \%\text{ equivalent of } (\text{VI}-1)/(\text{CI}-1) \tag{2}$$

$$\text{SSI (Standard Sinuosity Index)} = \text{CI}/\text{VI} \tag{3}$$

where CI is channel index (CL/Air), VI is the valley index (VL/Air), CL is the length of the channel (thalweg) in the stream under study, VL is the valley length along a stream, the length of a line which is everywhere midway between the base of the valley walls (in this

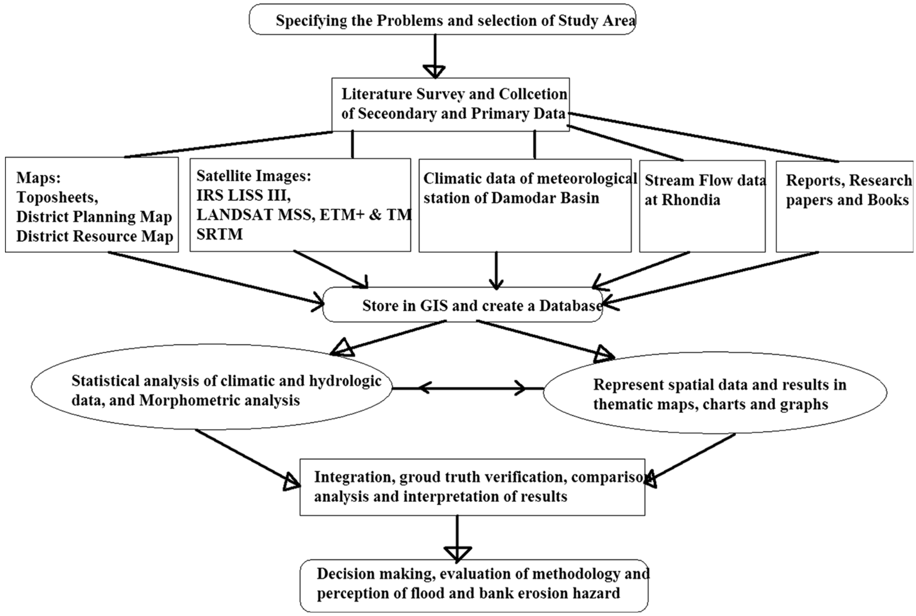

Fig. 1 Flowchart of adapted methodology

case, one half of total length of right and left banks of a reach), and Air is the shortest air distance between the source and mouth of the stream (in this case shortest air length of a reach) (Mueller 1968; Prasad 1982).

Brice's braiding index can be defined as

$$\mathrm{BI} = 2\left(\sum L_{\mathrm{i}}\right)/L_{\mathrm{r}} \tag{4}$$

where L_{i} is the length all islands and bars in the reach and L_{r} is the length of the reach measured midway between the banks of the channel belt (Brice 1964).

Braid-Channel Ratio of Friend and Sinha (1993) has been measured as follows

$$\mathrm{B} = L_{\mathrm{ctot}}/L_{\mathrm{cmax}} \tag{5}$$

where L_{ctot} is the sum of mid-channel lengths of all the segments of primary channels in a reach and L_{cmax} is the mid-channel length of widest channel through the reach (Friend and Sinha 1993).

To estimate the carrying capacity (m^3) of a particular segment and threshold level of flood discharge or bankfull discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$), we have calculated mean cross-sectional area (m^2) and mean maximum length of the reach (m) of three selected channel segments of Damodar River, viz. (1) Rhondia to Jujuti segment, (2) Jujuti to Chanchai segment, and (3) Chanchai to Paikpara segment, using SRTM data and Global Mapper 13.0 software (3D path profile tool).

After collecting the results, we have employed different statistical analysis and graphs, viz. mean, standard deviation (σ), coefficient of determination (R^2), Pearson product moment correlation (r), regression, log Pearson Type III probability distribution, Gumbel distribution, etc., for hydrological interpretation of stream flow data. In flood frequency analysis of stream flow data, the exceedence probability (P) can be defined by Gumbel distribution as

$$\mathrm{P} = 1-\mathrm{e}^{-\mathrm{e}-\mathrm{y}} = 1/T_{\mathrm{r}} \tag{6}$$

where T_{r} is return period, y [here, $y = a\ (x-x_{\mathrm{f}})$] is called reduced variate, a and x_{f} (a reference value of x) are the parameters of the distribution which can be obtained from sample statistics through the method of moments (Reddy 2011). If X_{T} denotes the magnitude of the flood with return period of T_{r} years,

$$X_{\mathrm{T}} = X_{\mathrm{mean}} + K_{\mathrm{T}}.\sigma \tag{7}$$

where K_{T} is the "frequency factor" ($y_{\mathrm{T}-}y_{\mathrm{mean}}/\sigma_{\mathrm{n}}$), y_{T} is the reduced variate, y_{mean} is the mean of reduced variate, and σ_{n} is standard deviation of reduced varites (calculating these from table value of Gumbel's distribution) (Reddy 2011).

Logarithmic Pearson Type III distribution (LP3) of flood frequency has advantage of providing a skew adjustment and if the skew is zero, the log Pearson distribution is identical to the log Normal distribution (Rao and Hamed 2011; Raghunath 2011). The probability density function for type III (with origin at the mode) is

$$f(x) = f_{\mathrm{o}}(1-x/a)^{\mathrm{c}}\exp(-cx/2) \tag{8}$$

where

$$c = 4/\beta - 1, \quad a = (c\,/\,2)(\mu_3/\mu_2), \quad \beta = \mu_3^2/\mu_2^2 \tag{9}$$

$$f_o = (n/a)\left[c^{c+1}/\mathrm{e}^c\Gamma(c+1)\right] \tag{10}$$

where μ_2 is the variance, μ_3 is third moment about the mean ($\sigma^6 g$), E is the base of the Napierian logarithms, Γ is the gamma function, n is the number of years of record, g is the skew coefficient, and σ is the standard deviation (Rao and Hamed 2011). The United State Water Resource Council (USWRC 1967) and Haan (1977) adopted that distribution to achieve standardization of procedures. The values of x for various recurrence intervals are computed from

$$\log x = \log x_{\text{mean}} + K_T \sigma_{\log x} \tag{11}$$

where K_{T} is the frequency factor, tabulated in respect of skew coefficient and recurrence intervals (Haan 1977).

3 Damodar River Basin

The Damodar River rises in the Khamarpat Hills of Chotanagpur Plateau (near Chandwa in Palamau district, Jharkhand) approximately at 23°37′N and 84°41′E (Sen 1985; Ghsoh 2011; Bhattacharyya 2011). For the first 45 km, the river is known as *Deonad*. The Damodar—the name originating from *dam* + *udar* (the river with a fiery belly, possibly symbolizing the existence of coal in its valley) as claimed by the agricultural settled caste Hindus who belong to the upper crust of modern Indian society, or *dah* + *modar* (sacred water) as claimed by local *adivasi (i.e., tribe)* folklore (Lahiri-Dutt 2003).

The Damodar River is a tributary of the Bhagirathi-Hooghly River system of West Bengal, carrying coarse sediments from Chotanagpur Plateau to the western part of Bengal Basin (Fig. 2). Its funnel-shaped basin area is about 23,300 km^2, in the states of Jharkhand (73.7 % of basin area) and West Bengal (26.3 % of basin area) (Majumder et al. 2011). Near Palla village (close to Chanchai rail station), the lower reach of Damodar takes a sharp southerly 90° bend (fault guided) and below Paikpara, the Damodar River bifurcates into the Kanki-Mundeswari and the Amta Channel-Damodar and joins with Hooghly River at Falta some 48.3 km south of Kolkata City (Bhattacharyya 2011; Ghosh and Mistri 2012a). Damodar River had been deeply incised in the faulted Gondowana uplands of Jharkhand, following Raniganj coal belts and lateritic *Rarh Plain* of West Bengal, and after which it had formed older alluvial plain of Late Pleistocene and Early Holocene ages (Sijua Morpho-stratigraphical unit), respectively, in the lower valley, developing a fan-delta toward east (Acharyya and Shah 2007).

For field investigation (sample study), we have selected the lower flood-prone segment (23°00′–23°22′N and 87°28′–88°01′E) of Damodar River (82 km length) in between Rhondia and Andersion Weir below Durgapur Barrage (west) and Paikpara below Jamalpur (east) (Fig. 1). Based on channel dimensions (i.e., width–depth ratio, sinuosity, entrenchment, braiding, river cross-sections, etc.) the channel is subdivided into four broad segments for fled study, viz. (1) Rhondia to Kashpur, (2) Kashpur to Idilpur, (3) Idilpur to Chanchai), and (4) Chanchai to Paikpara. Using Landsat satellite image and GPS device (UTM projection and WGS-84 datum), the field cross-profiles of Damodar River are drawn in selected points to delineate channel shifting, and the vulnerable locations of bank erosion are also revisited through GPS survey and Google Earth imagery. The GPS survey is started from a control base point of known bench mark nearer to the Damodar River, and the elevations of sample nodes are sequentially stored in the device, plotting these in Landsat image and Google Earth to analyze the survey path.

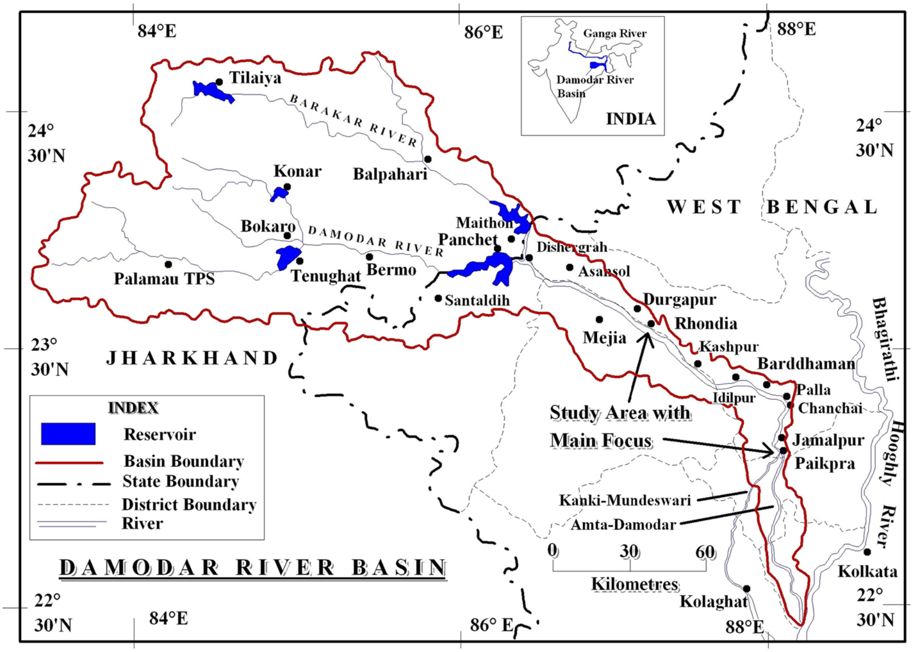

Fig. 2 Location map of DRB including study area

In lower DRB, the records of floods for the period between 1878 and 1912 are not complete, but few written documents of furious floods were reported in 1882, 1890, 1898, 1901, 1902, 1903, 1905, and 1907 (Peterson 1997). The flash floods of 1823, 1840, 1913, 1935, 1941, 1958, 1959, and 1978 had peaks of more than 16,992 m^3 s^{-1} (Mukhopadhyay and Dasgupta 2010; Bhattacharyya 2011). The flood of Damodar River comprises two main phases, viz. "the land phase" where prolong rainfall and infiltration excess overland flow generate flood and "the channel phase" which follows the land phase closely and starts when surface runoff enters the stream channels. Ordinarily when speaking of floods, we mean the channel phase is the most spectacular and on the whole the most destructive (Sarma 2002).

4 Damodar Valley Project

Conceived in 1945 on the lines of Tennessee Valley Authority (TVA), the Damodar Valley Corporation (DVC) was formed in 1948 (Bhattacharya 1959). After the devastating flood of 1943, the British Bengal Government set up a "Damodar Flood Enquiry Committee," which advised that nothing less than a complete catchment-basin scheme could prevent further destructive flooding by the Damodar in West Bengal (Krik 1950; Saha 1979). It was decided that the scheme had to be implemented through eight large dams at eight sites, viz. Tilaiya, Maithon and Balpahari on the Barakar River; Bokaro on the Bokaro River; Konar on the Konar River, and the Panchet, Aiyer, and Bermo detention dams (Krik 1950; Chandra 2003). But in the first phase, only four dams (Fig. 3, 4), viz. Tilaiya (1953), Konar (1955), Maithon (1957) and Panchet (1959), had been constructed by DVC (Table 1).

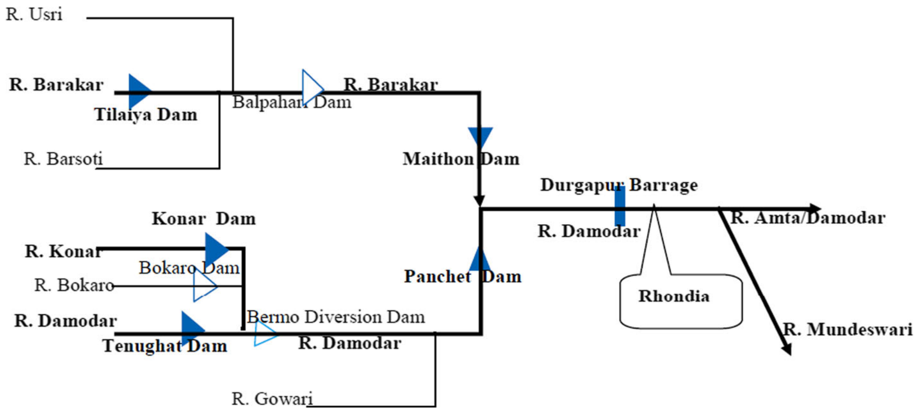

Fig. 3 Present form of DVC controlled structures on DRB (after Keshri et al. 2012)

Fig. 4 **a** Panchet dam on Damodar River, **b** Maithon dam on Barakar River, and **c** Anderson weir on Damodar River at Rhondia (daily discharge measuring station in Lower Damodar Valley)

Then, one more reservoir, Tenughat (1974) on Damodar under control of Jharkhand and Durgapur barrage (including main left bank and right bank irrigation canals) (1955) under control of West Bengal are constructed (Chandra 2003).

5 Influence of infrastructures on hydrogeomorphology of Damodar River

Since ancient times, the river flood and control structures have been the basis for riverine civilizations of riparian landscapes (Bagchi 1977; Bhattacharyya 2011). One can argue that civilization as we know it would not have arisen without river control. Dams continue to act as bulwarks against catastrophic flood destruction all over the world, and river control structures have formed the mainstay of planning program and self-reliance in developing countries (Bhattacharyya 2011). Despite the enormous benefits but short-term sustainability, these structures violate the environmental ethics and natural balance in the fluvial system. The drastic modifications of DRB have arisen a number of problems which are linked with hydrogeomorphic responses, intensifying the downstream flood propensity at present (Sanyal et al. 2013). The following analysis is mainly centered on changes in stream flow, bank erosion, channel shifting, channel planform, paleochannels, siltation of reservoirs, and river and flood risk, etc., that have occurred in response to river regulation, derived from comparisons of data observed during the pre-dam era (1933–57) and the post-dam era (1958–2007) (Fig. 5).

5.1 Embankments and responses of river

In the southern part of West Bengal, the history of earthen embankments predates to British rule (Bhattacharyya 2011). According to Bhattacharya (1959), these embankments are more than 1,000 years old. The agricultural prosperity of Damodar floodplain has continued for centuries (renowned as "Rice Bowl of West Bengal"), and these earthen embankments (locally known as *Boro Bandh*) were intended to save the paddy crop, as well as to protect the towns and villages in monsoon season (Bhattacharyya 2011). The left bank embankment of Damodar River was constructed from 93 km away of Dishergarh (confluence point of Barakar and Damodar), and its height is increased downstream in post-dam period. After devastating flood of 1885, the height of left side embankment around Barddhaman town was further increased and the embankment of right bank was demolished (Bhattacharya 1959). Lower Damodar Scheme (sanctioned in 1971) was developed to mitigate the monsoonal flood problems and to improve drainage condition in the trans-Damodar area (includes the districts of Barddhaman, Hooghly and Howrah). This scheme remodeled the left embankment by boulders and sand bags, including longitudinal and transverse dykes. Part of the valley is still inundated when earthen embankment of right bank is frequently breached or the flood water is overtopped. This phenomenon expresses the power of Damodar flood, and it gives birth to several spill channels, locally known as "*hanas*" (e.g., Deb Khal) (Fig. 6).

Embankments constrict the active floodplain in lower DRB and compel the river dissipate its energy within the narrow sandy bed. In the post-dam period, the controlled flood discharge of the braided Damodar River is unable to access floodplain and deposition takes place on the river bed itself, forming longitudinal bars, mature point bars, and islands (e.g., Bara Mana, Majher Char, Fatepur Mana, etc.). According to Bhattacharya (1959) carrying a large volume of coarse sediments from the Archean plateau and Raniganj coal belt, the Damodar River is now in aggradational phase within embanked river bed and the siltation raises the elevation of bed in respect of adjacent less flooded alluvial plain. It has been estimated that in a year, 3.10 tons of sediments is carried by Damodar River up to Anderson Weir, Rhondia (Rudra 2010). It should be remembered that this amount of sediments is reached to that location after crossing the big burdens of five upstream reservoirs and Durgapur Barrage (Rudra 2010). Therefore, the threshold level of bankfull discharge is getting lower and lower in this segment. In between the stretch of Jujuti (23°15′22″N, 87°44′03″E) and Hatsimul (23°12′17″N, 87°53′30″E), the height of embankment ranges from 7 to 13 m from local datum level (using GPS survey). Side by side the river deposits sands with a thickness of 4.5–7.5 m from the base of previous embankment. So it has been found that in some areas of lower DRB, the present river bed (adjacent to bank) is increased up to 2–3 m from the adjoining floodplain. Again increasing the length of bars and islands, growth of vegetation on these, and stabilization of dunes and point bars signify the degree of siltation and low limit of activeness of river in the post-dam period. Since the right bank is not protected, there is continuous deposition in the floodplain of right bank and the altitude of levee is increased step by step (Fig. 6). As a consequence, the right bank floodplain has become higher, and it forces the shifting of thalweg to move northward in high discharge period, creating more pressure on left

Table 1 Summary of DVC dams in the DRB

Dams/barrage	District and state	River	Year	Type	Height (m)	Length (m)	Power generation (MW)	Irrigation storage (million m3)	Flood storage (million m3)
Tilaiya	Koderma, Jharkhand	Barakar	1953	Concrete gravity dam	30.28	366	2 × 2 MW	141.86	177.63
Maithon	Dhanbad, Jharkhand	Barakar	1957	Concrete gravity dam	50	4789	3 × 20 MW	611.84	542.76
Panchet	Dhanbad, Jharkhand	Damodar	1959	Earthen dam with concrete spillways	45	6777	2 × 40 MW	228.21	1086.8
Konar	Hazaribagh, Jharkhand	Konar	1955	Concrete gravity dam	48.77	4535	–	220.81	55.51
Tenughat[a]	Bokaro, Jharkhand	Damodar	1978	Composite masonry cum concrete spillways	55.0	5000	–	–	–
Durgapur Barrage[b]	Barddhaman, West Bengal	Damodar	1955	Concrete and 34 gates including sluice	12.0	692	–	–	–

Source: DVC (2013), www.dvcindia.org/

[a] Total live storage of Tenughat dam is 224 million m^3 (without provision of flood storage); [b]lengths of left and right bank irrigation canal of Durgapur barrage are 136.8 km and 88.5 km respectively

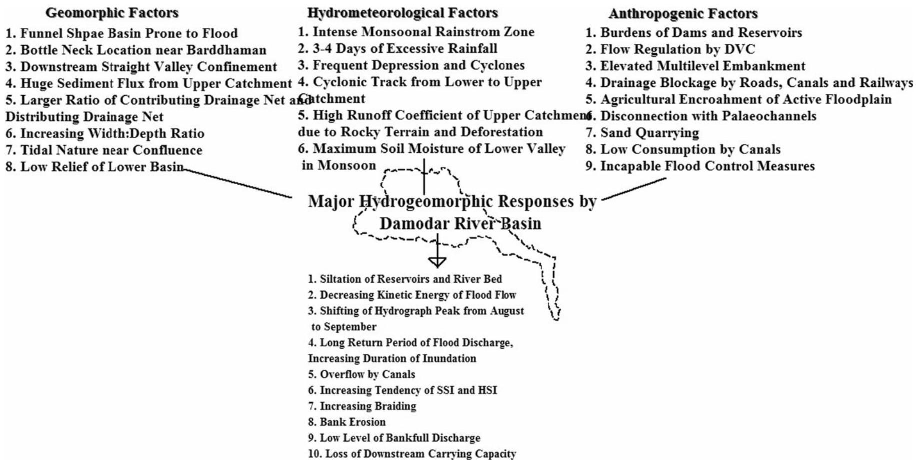

Fig. 5 Dominant factors of monsoonal floods and associated hydrogeomorphic changes in the DRB

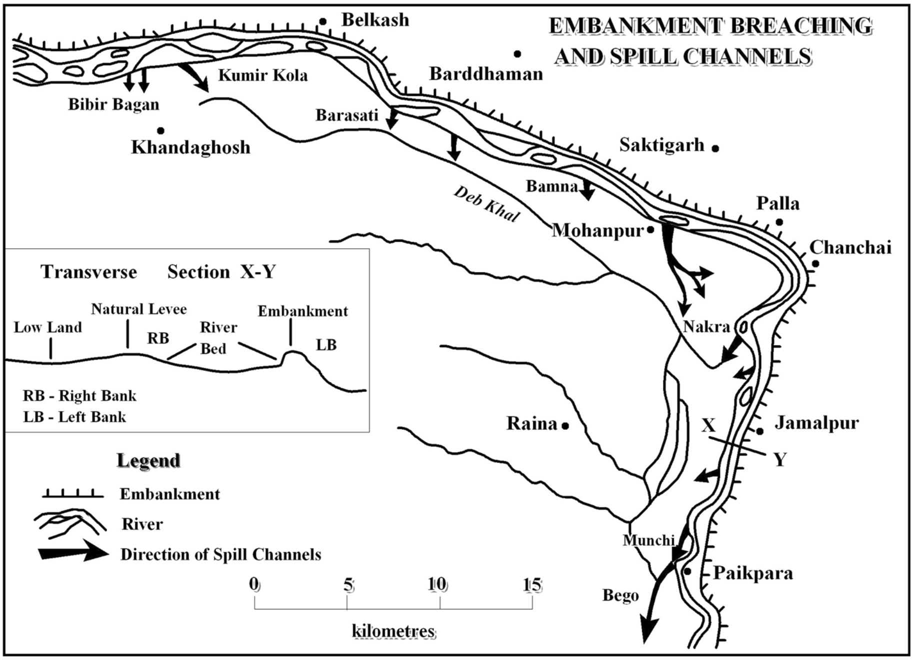

Fig. 6 Glimpses of spill channels in lower Damodar River denoting the sites of embankment breaching on right bank and paths of spill channels, and a cross-profile (*inset*) denotes rising height of right-side floodplain than left (after Bhattacharyya 2011)

embankment. This is evident from bank line shifting in Borsul, Palla, Hatsimul, etc. It is found that near Belkash, the Damodar River has shifted its permanent course up to 1 km toward right bank, creating an alluvial terrace at left bank (Fig. 7). Alongside other impacts of embankments are discussed in the later sections.

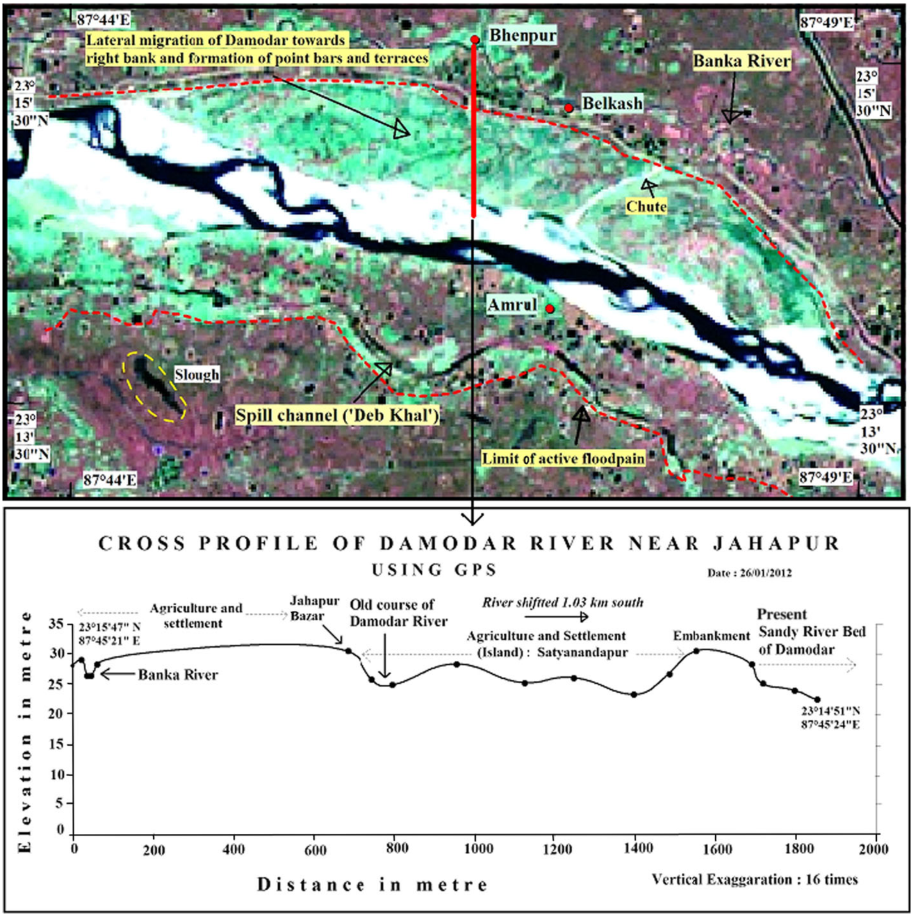

Fig. 7 Development of wide floodplain, spill channels, chute, sloughs, and point bars showing the high degree of aggradational landforms of Damodar River (FCC of Landsat ETM + , 2000) and Garmin GPS cross-profile (2012) showing post-dam expanse of river shifting and deposits of thick layered sands (stretch of 1.03 km) near Jahapur Bazar (previous embankment) in post-dam period

6 Results

6.1 Variation in stream flow

From the hydrographs based on the year-wise and month-wise stream flow data (1934–2007), it is cleared that at Rhondia, the Damodar River experiences a “Tropical Single Maximum with a Long Low Water” (A_W) regime or hydrological region (Beckinsale 1969). In the pre-dam period, the peak flows are observed in the month of August (on an average 1,238 $m^3 s^{-1}$) but after construction of dams the peak shifts from August to September (on an average 1,247 $m^3 s^{-1}$) (Fig. 8a). The main reason of that shifts is the installation of flood storage system of DVC. The dams temporarily store inflow runoff and streamflow till late August but due to continuation of unexpected heavy rainfall and critical reservoir storage limit, the dams are compelled to release water in September when the alluvial soils of lower DRB are gained full moisture and excess water adds with this streamflow. That is why now the flood probability or chances are more common in between September and October.

There is marked difference of annual peak flow (Fig. 8b) in between pre-dam (1933–1957) and post-dam period (1958–2007). A peak flow of above 18,000 m^3 s^{-1} has been recorded three times in August 1913, 1935 and October 1941 (Saha 1979; Bhattacharyya 2011). In post-dam period, the highest combined outflow from Maithon and Panchet dams had been generated a huge discharge of 21,070 m^3 s^{-1} on September 27, 1978, at Durgapur barrage. At present, extremely abnormal floods (8,496–12,744 cumec) are disappeared but the frequency of subnormal floods (below 5,664 cumec) is still remained high in lower DRB (Bhattacharyya 2011).

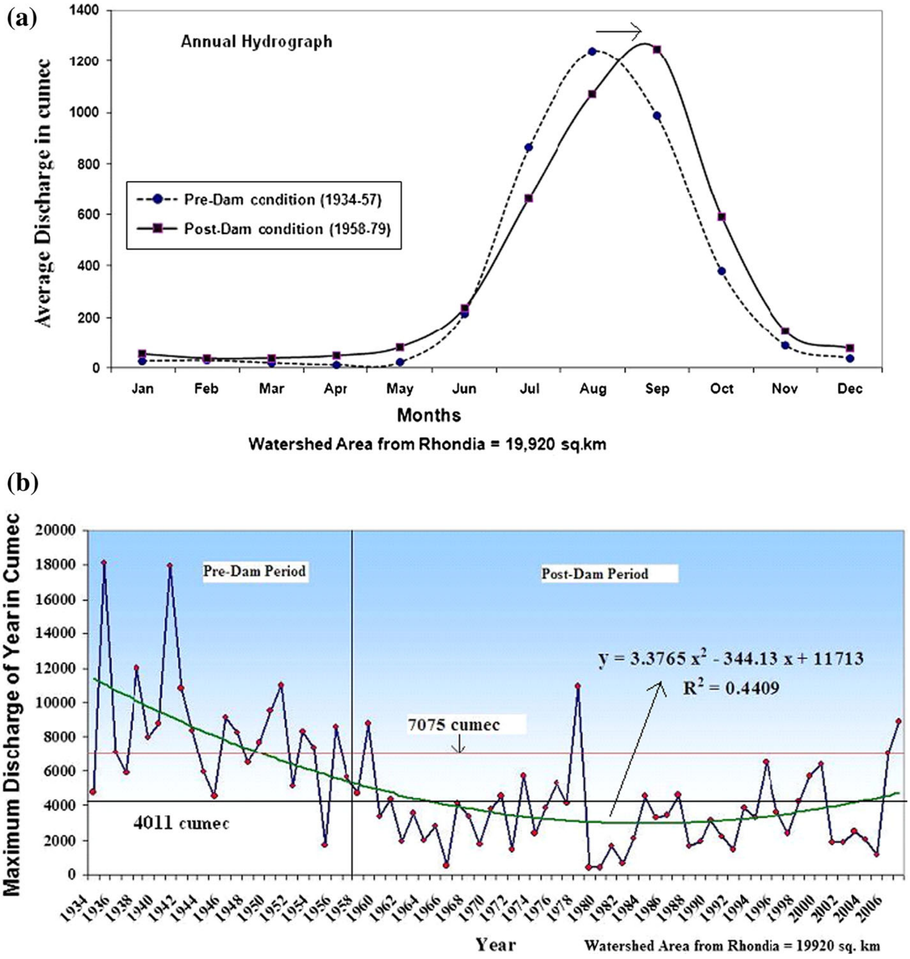

Fig. 8 **a** Annual hydrograph showing shift of peak flow from August (pre-dam) and September (post-dam) and **b** temporal variation of flood peaks (1934–2007) including two critical limits of bankfull discharge (at Rhondia) of 7,075 cumec (estimated by Voorduin in the time of dam construction) and 4,011 cumec (estimated by authors), respectively

Implementing log Pearson Type III Distribution in annual stream flow data of pre-dam period (1934–57), the peak discharge of 18,112 cumec (1935) has attained a return period of 50 years with 2 % of probability of occurrence. Alongside the selected peak discharges of 12,002 cumec (1938), 11,012 cumec (1951), and 10,811 cumec (1942) have attained only 6.7 years (15 %), 4.9 years (20.4 %), and 4.6 years (22 %) return periods, respectively. This signifies the low recurrence interval of high magnitude floods in the lower valley in between 1934 and 1955. Implementation of Damodar River Valley Project has radically altered the peak discharge value and recurrence interval through controlled regulation of water from last two terminal big dams (Fig. 9). Based on 50 years of database (1958–2007), the peak flood discharge of 10,919 cumec (1978) has attained a return period of 124 years with only 0.81 % of probability of occurrence, but it was only 4–5 years (22 % of probability) in pre-dam period. It signifies the performance of DVC in flood regulation. Now the return period of 2–2.7 years (50–37 % probability of occurrence) is associated with peak discharge of 2,811–3,855 cumec. Before the construction of DVC dams, the flood peaks were unusually high but the duration was small (late August to September). The dams have now moderated the peaks but increased duration of floods (August to October).

6.2 Changing channel pattern

To understand the influence of dams on the river, two indexes have been used—(1) sinuosity index and (2) braiding index. The hydrogeomorphic dynamics of river and other external factors directly distort its course from pervious path, and it is well measured by sinuosity index (Babar et al. 2012). The major attractiveness of Mueller's component of sinuosity index is that it accounts for what percentage of a stream channel's departure from a straight line course is due to either hydraulic factor within the valley or to topographic

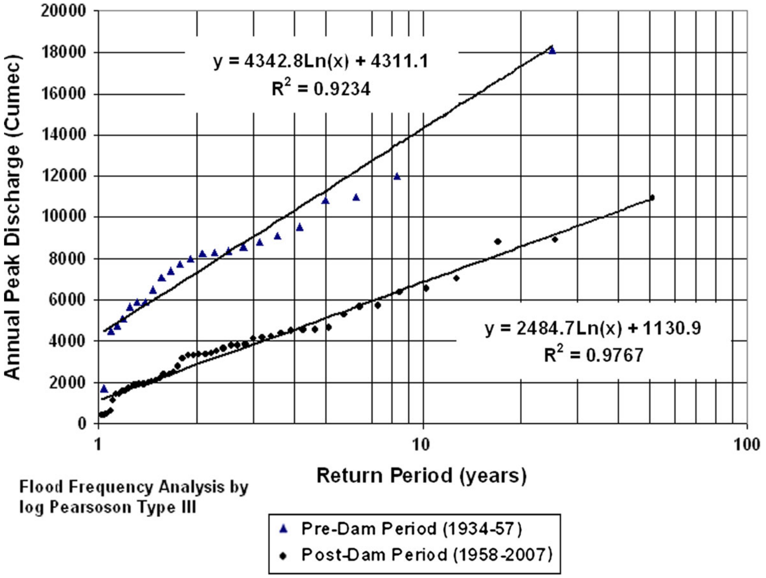

Fig. 9 Pre-dam and post-dam change in annual flood peaks and its associate recurrence intervals signifying the performance of DVC flood regulation system

interference. Mueller's sinuosity index (1968) includes the hydraulic sinuosity (i.e., that freely developed by the channel uninfluenced by valley-wall alignment) and topographic sinuosity (i.e., that imparted by the geometry of the valley) (Mueller 1968).

The Standard Sinuosity Index (SSI) (Fig. 10) varies from 1.01 (pre-dam) to 1.16 (post-dam) in between Rhondia and Paikpara (Table 2). The most important thing is that in pre-dam period (1922–43), Hydraulic Sinuosity Index (HSI) of four reaches is gradually decreased downstream from 48 percent to 13 percent, alongside Topographic Sinuosity Index (TSI) is increased downstream from 51 to 87 %. It signifies that in pre-dam phase (prevailing almost natural condition) sinuosity of Damodar River is mainly controlled by the topographic factors of floodplain, viz. fault-guided valley alignment (Singh et al. 1998), cohesive bank materials, less number of bars, coarse bed configuration, or neo-tectonic activity, not by solely monsoonal flood discharge and other hydraulic factors. But in post-dam period (especially in between 2001 and 2006), the sinuous pattern of Damodar River is achieved from downstream to upstream direction, and the most significant fact is that HSI is radically increased downstream in all four reaches (62–93 %) compared to TSI (7–38 %). Surprisingly in between Idilpur (23°14°53″N, 87°47°58″E) and Chanchai (23°17°38″N, 88°01′00″E), HSI has contributed 92 percent influence on sinuosity, and in between Chanchai and Paikpara, it is 85 percent. 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. As in the studies done by Sen (1985, 1991), Garde (2006), Ghosh (2011), and Bhattacharyya (2011), now the infrequent bankfull discharge, variable flow velocity, fluctuating monsoonal flow regime, high width–depth ratio, 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, sand quarrying, elevated concrete embankments and flow diversion through canals are the dominant hydraulic factors to deviate channel sinuosity in the downstream section (Ghosh and Mistri 2012b).

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). The

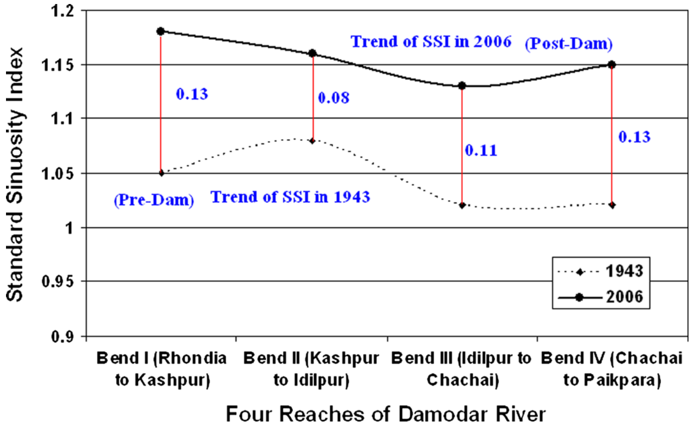

Fig. 10 Significant deviation of SSI (increasing value of sinuosity) in the four segments of Damodar River (Rhondia to Paikpara) in between pre-dam and post-dam periods

Table 2 Temporal variation of Mueller's Sinuosity indexes in Damodar River

Years	Bend I (Rhondia to Kashpur)			Bend II (Kashpur to Idilpur)			Bend III (Idilpur to Chanchai)			Bend IV (Chanchai to Paikpara)		
	SSI[a]	HSI[b] (%)	TSI[c] (%)	SSI	HSI (%)	TSI (%)	SSI	HSI (%)	TSI (%)	SSI	HSI (%)	TSI (%)
1922–43	1.05	48	51	1.08	39	61	1.02	34	66	1.02	13	87
1969–74	1.17	92	08	1.10	51	49	1.02	12	88	1.04	32	68
1990	1.10	59	41	1.09	60	40	1.02	72	28	1.02	13	87
2001	1.11	65	35	1.15	60	40	1.10	74	26	1.01	04	96
2006	1.18	71	29	1.16	62	38	1.13	93	07	1.15	85	15

[a] Standard Sinuosity Index

[b] Hydraulic Sinuosity Index

[c] Topographic Sinuosity Index

degree of braiding as displayed in the satellites images is well established by BR which is devised by P.F. Friend and R. Sinha (1993). Landsat TM images of 1990 and 2006 are used to calculate BR and BI in the selected segments (Table 3), viz. (1) Rhondia to Kashpur, (2) Kashpur to Idilpur, and (3) Idilpur to Chanchai. 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. 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 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 (Garde 2006; Bhattacharyya 2011). 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 (Fig. 7).

6.3 Fluvial aggradation and degradation

The paleoclimatic studies of India indicate that in the last 100 years, the periods of aggradation of Peninsular Rivers are linked to periods of weaker southwest monsoon and reduced sediment supply (Singhvi and Kale 2009). As the natural flow is regulated by DVC dams, the transportational energy of Damodar River is lost gradually in the immediate downstream of Durgapur barrage, and it also affects the sedimentation profile of bars

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

Year	Bend I (Rhondia to Kashpur)		Bend II (Kashpur to Idilpur)		Bend III (Idilpur to Chanchai)	
	BI[a]	BR[b]	BI	BR	BI	BR
1990	5.31	2.47	4.72	2.75	2.87	2.04
2006	4.4	2.13	3.91	2.08	3.03	1.37

[a] Braiding Index

[b] Braid-channel Ratio

(Bhattacharyya 2011). Few intra-bedded brown clayey silt and sandy silt deposits (near Rhondia) of recent Hooghly Morpho-stratigraphical Unit (HMU) (Acharyya and Shah 2007) signify infrequent extreme flood events (high level discharge) but thick deposit of clay and mud carries (Fig. 11) the indication of slow deposition (post-dam waning flood deposits) in more sub-humid monsoon climate. Disappearance of iron nodules and high proportion of silt in top lithofacies of Fm (Miall 1985) signifies the younger (post-dam period) fluvial deposits under stagnant water condition (suspended load) in the mature point bars of left bank. The facies of fine sand with clay partings (Sh) and small size gravel base (Miall 1985) carry the sign of lateral accretion and avulsion toward right bank of Damodar. It is evident that from Anderson Weir of Rhondia, the river was opened up much wider and its active channel had been maintained toward far left side in 1922–1943. After dam construction, the river now shifts toward far right bank side (evident in Landsat images), developing alluvial terraces and point bars on left bank side (Fig. 12). Close to Deulpara (23°17′58″N, 87°34′23″E), in between 1973 and 2006, thalweg of Damodar River shifts far north (left bank side) compared to position of 1922–1943. Near Silla (23°17′38″N, 87°34′23″E), thalweg again shifts toward right bank (meandering channel way) in 2006. For that reason, 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 (23°20′35″N, 87°30′48″E), Fatepur Mana (23°15′39″N, 87°36′25″E), Sadpur Mana (23°20′06″N, 87°32′09″E), etc.

Near Satyanandapur (23°15′22″N, 87°46′38″E), in 1972–1974, the river was more constricted toward its right side, but in 1990 and 2006, channel shifts to north nearer of left side embankment. After that, it tends toward right side bank creating elongated Majher Char (23°14′21″N, 87°40′04″E). The most vulnerable locations of bank erosion are Ghoradanga (23°17′48″N, 87°32′30″E), Baikuthapur (23°14′15″N, 87°36′01″E), Somsar (23°13′29″N, 87°38′27″E), Beldanga (23°13′30″N, 87°39′41″E), Dadpur (23°07′16″N, 87°39′41″E) (Bankura district), and Lakshmipur village (23°05′49″N, 87°59′28″E) (Barddhaman district). The flow is restricted near Sadarghat (23°12′44″N, 87°50′56″E) due to construction of Krishak Setu or Bridge (Fig. 13). But after crossing the bridge, it opens up widely and erodes its right bank at Bangachha village, near Jamalpur (23°03′40″N, 87°59′34″E). Then, the river erodes its left bank near Hatsimul and Belna (23°11′57″N, 87°56′10″E) (Fig. 10). Within its narrow active space of elevated embankments (from Barsul to Paikpara), the river alters its active thalweg frequently in a

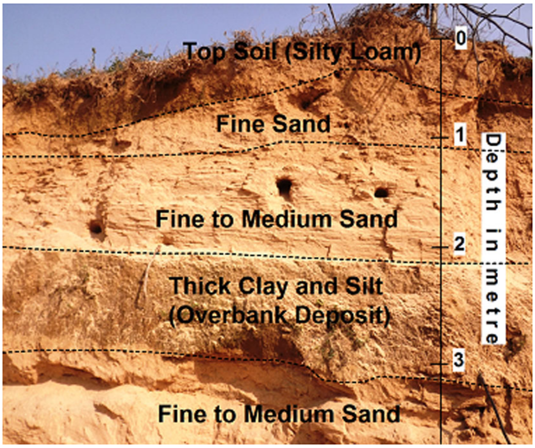

Fig. 11 Litho-unit (Hooghly Morpho-stratigraphical Unit) of left river bank of Damodar at Rhondia, showing fluvial succession of bottom fine to medium sand (Sh), thick overbank brownish clayey silt (Fsc), and fine sand with top clayey silt layer (Fm)

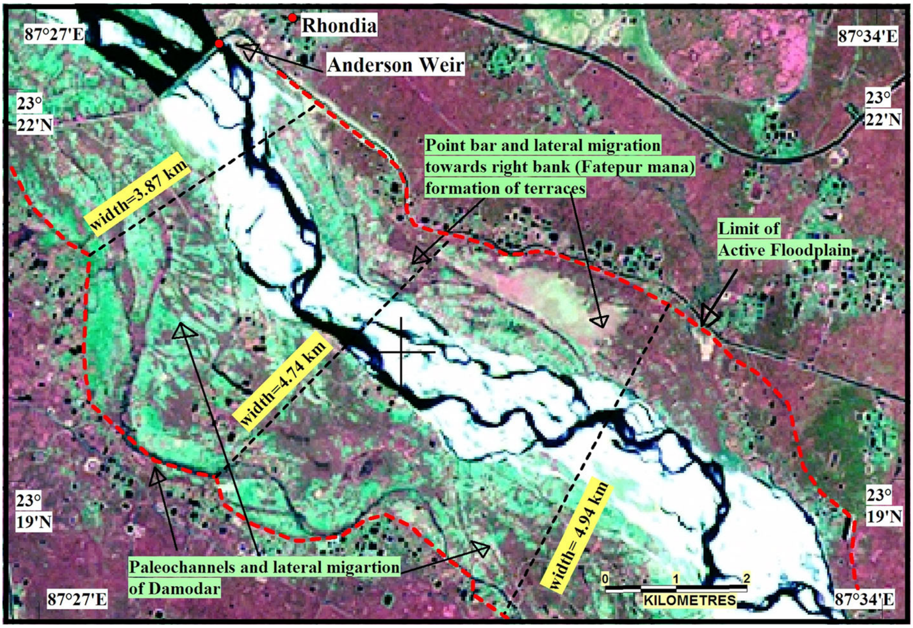

Fig. 12 Glimpses of widely active floodplain (up to 5 km width), spill channels, avulsion, alluvial terraces (now used as arable land), and mature point bars showing the high degree of lateral oscillation and aggradation of Damodar River in the immediate downstream of Rhondia (FCC of Landsat ETM + , 2000)

meandering pattern and changes its aggradational and degradational processes in slip-off slope and cutoff slope, respectively. In 44 years (1972–2006), the lands lost, due to bank erosion of Damodar, 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. The present study reveals that the river in between Rhondia and Barddhaman shows dominance of aggradational landforms, braiding, erosion of right bank, and valley widening but downstream of Barsul (23°11′02″N, 87°57′56″E) and Chanchai the bank erosion, high sinuosity and narrowness are more pronounced.

6.4 Post-dam change in Flash-Flood Magnitude Index

Flash floods are usually caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours and are characterized by raging torrents after heavy downpours that rip through the river beds, agricultural fields, urban streets or hilly tracts sweeping everything before them (Ward 1978; Allaby 2006). Recent disastrous flash flood of Uttarakhand and Himachal Pradesh (14–17 June, 2013), due to cloud burst and breaking of moraine dam, is forced to think about the magnitude, extremity, and time of occurrence of sudden floods in the heavy monsoon and rainstorm-dominated region of India, like West Bengal and eastern part of Jharkhand (Kale 2003; Dhar and Nandargi 2003; Nandargi and Dhar 2003). While floods in the major rivers cause extensive destruction in their floodplains, intense rainfall in the comparatively small catchments of many rivers, especially in the sub-mountainous or plateau scarp regions, cause flash floods (Singh et al. 1974). The giant volume of excess runoff is getting speed and momentum when the Damodar River has crossed the scarp of Chotanagpur Plateau, along Panchet and Maithon dams. In a

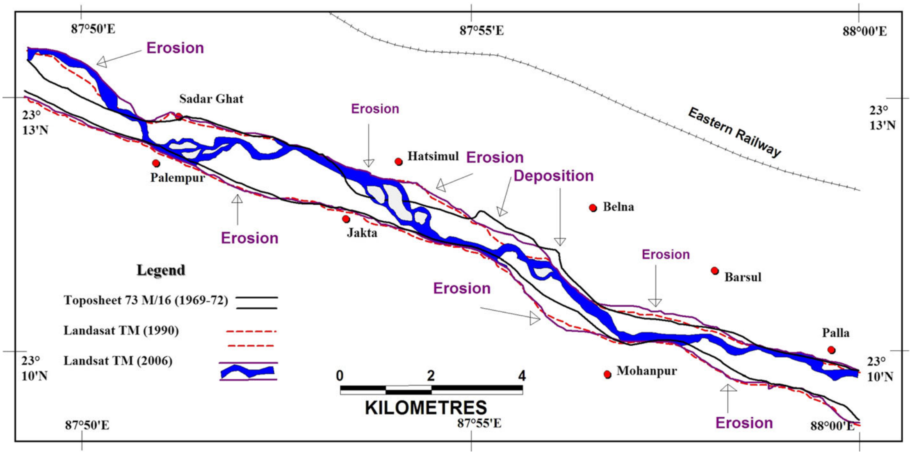

Fig. 13 Temporal change of Damodar River banks from Sadarghat to Palla (1972–2006)

monsoon-dominated and cyclonic-affected region, the higher contributing drainage network and the lower distributing drainage network (found in DRB) aggravate the chances of flash floods (Sengupta 2001), and abrupt relief difference (i.e., break of slope) along Maithon and Panchet dams (Saha 1979) provides additional power to flood flows. In old records, the Damodar River has always been referred to as a "river of sorrow" for to its recurrence extreme floods due to heavy rainfall. To describe the flood ferocity and adamant nature of Damodar, W. W. Hunter in 1876 wrote that during monsoon floods, the rainwater used to pour off the hills through hundreds of channels with such suddenness that water heaped up to form dangerous head waves known as "*harkaban*" (i.e., flash flood) (Lahiri-Dutt 2006; Bhattacharyya 2011).

The absolute flood discharge of a river is not as important with regard to geomorphic change as the ratio between peak discharge and mean annual discharge (Patton and Baker 1976; Kochel 1988). Floods likely to result in significant geomorphic change are those that produce discharges many times above that normally experienced by the river, that is, those with high maximum peak discharge to mean annual discharge (Kochel 1988). Kochel (1988) and Kale (2003) have applied a parameter called the Flash-Flood Magnitude Index (FFMI) which is employed here for annual peak discharge analysis of lower Damodar Basin to understand the change in pre-dam and post-dam period at Rhondia (Table 4).

The FFMI is calculated from the standard deviation of the logarithms of annual maximum discharge as illustrated (Kochel 1988).

$$\mathrm{FFMI} = X^2/(N-1)$$

where $X = X_m - M$, X_m = annual maximum discharge, M = mean annual discharge, N = number of years of record, and X, X_m, and M = logarithms.

The index nearer to 1.0 or above indicates the high degree of flash flood with some geomorphic change within the basin (Kochel 1988). Log deviation from mean discharge to extreme peak value is exponentially ($Y_c = 0.1525 \times {}^{2.04}$) related to FFMI (Fig. 14a). It means the episodes of high degree of deviation between X_m and X are associated with high FFMI and extreme floods in Damodar River, having coefficient of determination of 0.96. FFMI gained maximum value in between 1950 and 1957 (pre-dam phase) and consecutively in between 1958 and 1969 (post-dam phase) (Table 4). Then, 33 years (1970–2003)

Table 4 Calculation of FFMI for Damodar River at Rhondia (1934–2007)

Year	X_m[a]	Date of X_m[b]	M	X	FFMI
1934–41	4.258	12/07/1935	2.422	1.836	0.482
1942–49	4.254	10/08/1942	2.577	1.677	0.402
1950–57	4.042	11/09/1951	1.321	2.721	**1.057**
1958-69	3.944	02/10/1959	1.164	2.780	**1.104**
1970–77	3.724	13/10/1973	2.392	1.332	0.253
1978–87	4.038	27/09/1978	2.190	1.849	0.488
1988–95	2.549	29/09/1995	2.278	0.272	0.011
1996–2003	3.805	23/09/2000	2.370	1.435	0.294
2004–07	3.949	25/09/2007	2.300	1.649	**0.907**

Bold portions are identified as major high FFMI period in between 1934 and 2007

[a, b] *Data source* Bhattacharyya (2011)

of record shows that FFMI was significantly low than pervious, that is why in these years no extreme floods (except 1978) had been occurred. But the last FFMI (2004–07) is approaching toward one which signifies forthcoming flash-flood episodes following the years of 2006 (7035 $m^3 s^{-1}$) and 2007 (8853 $m^3 s^{-1}$). It is important to note that the floods of peak flow of 8,496 cumec or more had been occurred 37 times between 1823 and 2007 (Bhattacharyya 2011). Average FFMI of Damodar River is getting value of 0.56 which is much greater than world average 0.278 and other Indian Rivers, viz. Narmada, Ganga, Godavari, Brahmaputra, Teesta, and Tapi. (Kale 2003). In general, the streams with extremely high FFMI occur in semi-arid region but interestingly in this monsoonal climate we have observed glimpse of flashiness in respect of other Indian rivers (Fig. 14b).

6.5 Declining carrying capacity and flood hazard

After installations of dams and barrage, unpredictably the lower DRB is not safe from floods. This statement can be validated from the acute flood years of 1959, 1978, 1995, 1999, 2000, 2003, 2006, 2007, 2009, and 2011 (Sanyal et al. 2013). It reflects that lower segment of Damodar River (including Amta channel and Mundeswari) has lost its previous carrying capacity to accommodate huge volume of flood flow in monsoon. Bankfull volume of a segment can be expressed in one cumec day (m^3) (Reddy 2011). If this total volume of water passed from a reach having a rate of 1 $m^3 s^{-1}$ is regarded as 1 cumec day $= 1 \times 24 \times 60 \times 60 = 86{,}400$ m^3, it can be assumed that in a day 86,400 m^3 of water is passed having a flow rate of 1 $m^3 s^{-1}$ in a particular segment of the river. Reddy (2011) has developed the following expressions.

Carrying capacity (m^3) = Mean cross-sectional area × Mean maximum length of a reach.

Bankfull flood discharge ($m^3 s^{-1}$) = Carrying capacity of a reach × 1 $m^3 s^{-1}$/86,400.

Importantly we have estimated three bankfull discharges of aforesaid segments which are 4,011 $m^3 s^{-1}$, 2,366 $m^3 s^{-1}$, and 1,542 $m^3 s^{-1}$, respectively (Table 5). Considering the DVC mentioned critical discharge limit of 7,079 m^3s^{-1}, it is very essential to find out the probable return periods of the four bankfull discharges (flood discharges) using the post-dam annual flood series and the methods of flood frequency analysis (Gumbel distribution, log Pearson Type III distribution, Chow's method and Stochastic method) (Table 5). From the

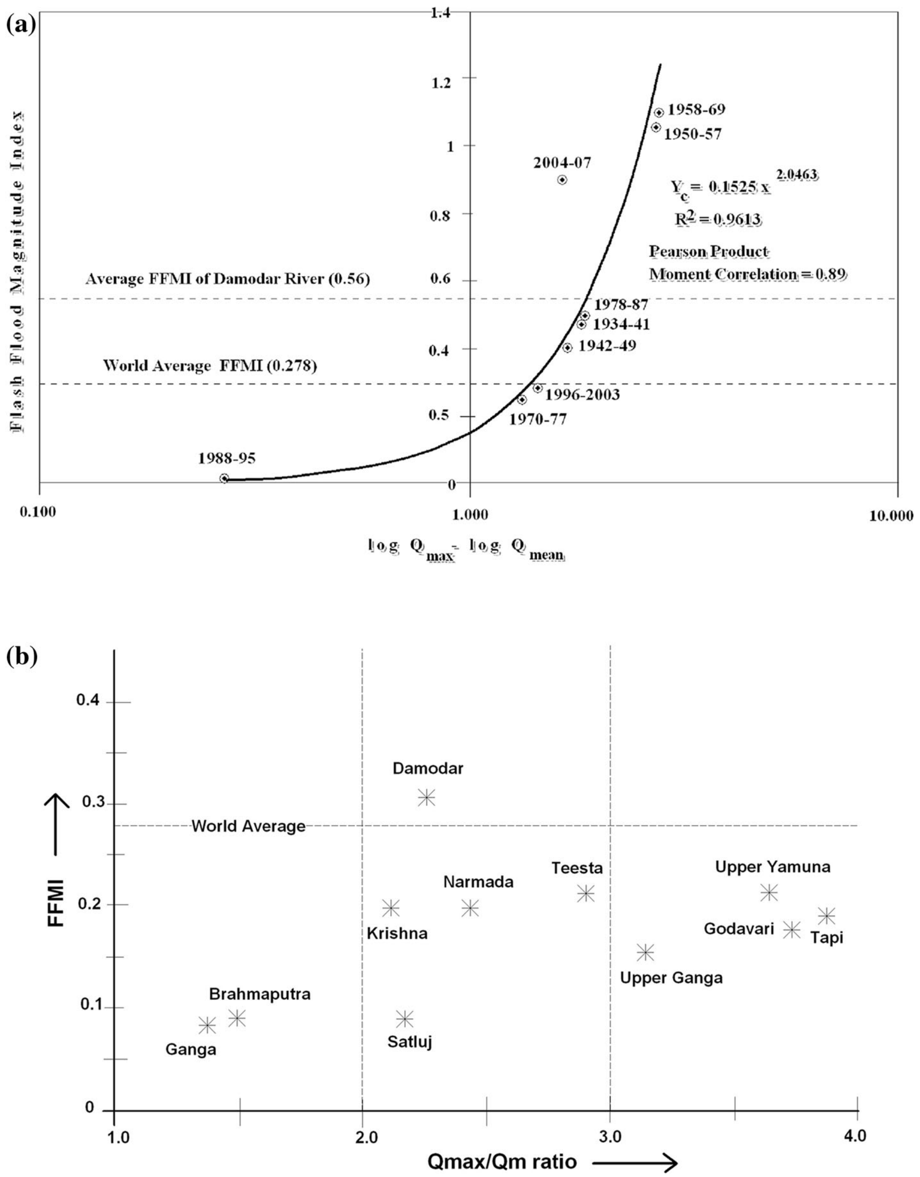

Fig. 14 **a** Deviation from mean discharge to extreme peak value is exponentially related to FFMI, i.e., high degree of log deviation is ultimately transformed into high magnitude of flash floods in lower Damodar River in post-dam period (1958–69 and 2004–07), **b** comparing FFMI (*Y*) and $Q_{\max}/Q_{\mathrm{m}}$ ratio (*X*) of Damodar with other Indian rivers, reflecting high degree of FFMI (after Kale 2003)

table, it has been found that the return period of 7,079 $m^3\ s^{-1}$ discharge ranges from 8.55 to 14 years at Rhondia. Similarly, the other return periods of three discharges range from 1.18 to 3.18 years. So it is clear that the threshold level of peak discharge (with short time span) is very small in respect of the post-dam annual flood series and carrying capacity of Damodar River. For that reason whenever the last two terminal dams (Panchet and Maithon) released

Table 5 Predicted return periods of probable bankfull discharges in Damodar River

Bankfull discharge in cumec	Estimated return period in years Gumbel	LP3[a]	Chow	Stochastic
7079	14.0	13.2	14.2	8.55
4011	2.90	2.92	2.91	3.18
2366	1.45	1.56	1.48	1.87
1542	1.21	1.18	1.23	1.44

[a] LP3 is the log Pearson Type III Distribution

excess water, inevitably the riparian tracts of Barddhaman, Hooghly, and Howrah Districts (covering lower DRB) had been experienced monsoonal floods for long days. Alongside high settlement density in adjoining floodplain, drainage congestion, and decaying of paleo-channels have aggravated the problem into misery. The capacity of Amta channel (present lower Damodar) and Mundeswari is now restricted to 849 $m^3 s^{-1}$ and 2,832 $m^3 s^{-1}$, respectively. In view of the above, moderation of 28,317 $m^3 s^{-1}$ flood or the known floods with a peak flow of 18,406 $m^3 s^{-1}$ to the present safe carrying capacity of 3,681 $m^3 s^{-1}$ of the channels in the lower Damodar is not possible at present (Keshri et al. 2012). Therefore, the good effects of the dams are not being felt by the population of the area. If the annual flood series follows the trend of post-dam period, the 5-year flood will be above 5,300 $m^3 s^{-1}$ and 100-year flood will be above 11,000 $m^3 s^{-1}$. As the rainfall, runoff, and flood flow are purely random phenomenon and the flood controlled system has certain limitations (in terms long-term sustainability), we cannot expect that the peak discharge of 10,919 $m^3 s^{-1}$ or more (1978) will not happen in the forthcoming years.

7 Discussion

7.1 Siltation of reservoirs

The proposed project of DVC was set forth to provide a controlled storage capacity of 6,500 million m^3 but only four dams and Tenughat reservoir provide a maximum storage capacity of 3,591 million m^3, only 55 % of storage capacity originally envisaged (Saha 1979). The last two terminal dams, Maithon and Panchet, are located close to break of topographic slope in the border of Jharkhand and West Bengal. So, the upstream tributaries of Damodar and Barakar bring heavy sediment laden water to these reservoirs, and the siltation of reservoirs is emerging as a major problem to affect the downstream flood control measures (Basu 2011). According to Lal et al. (1997), the siltation rate of Maithon and Panchet reservoirs is 1310.0 and 1059.0 $m^3 km^{-2}$/year, respectively. A recent study shows that the sedimentation of Panchet (on the basis of Landsat TM images of 1990 and 2005) occurs approximately at a rate of 0.041–0.047 cm per year, whereas it was 0.033 to 0.034 cm per year in 1990 (Majumder et al. 2012). If we consider the overall capacity (including dead zone, live zone, and flood zone), the loss of capacity of Maithon and Panchet reservoirs is 22.1 % (up to 1994) and 14.1 % (up to 1996), respectively (Rudra 2002; Bhattacharyya 2011). The temporal variation of flood moderation by Panchet and Maithon dams shows that there is now a declining trend of flood controlling performance till 2007 (Ghosh and Mistri 2013c). It is a reality that DVC dams cannot attain their

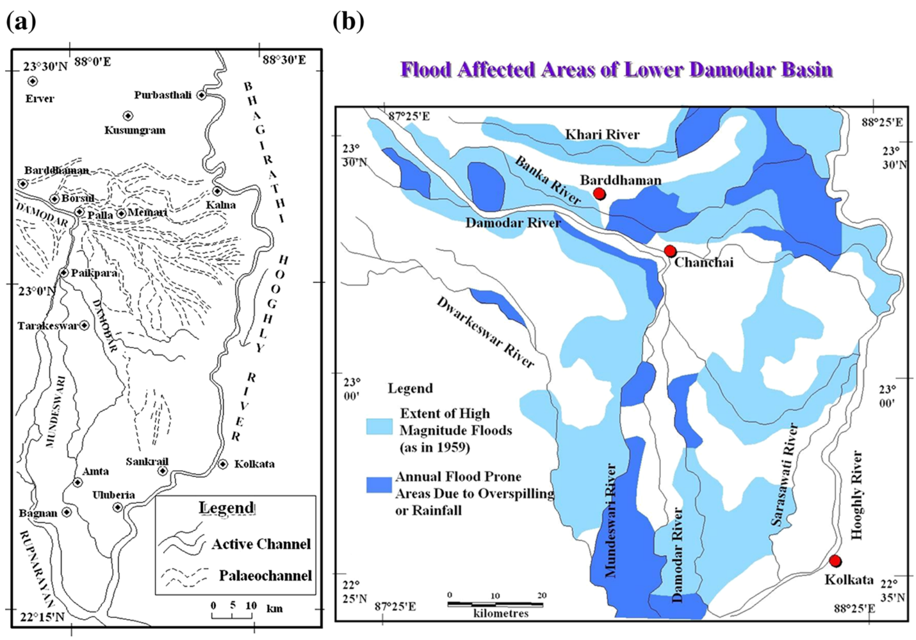

Fig. 15 **a** Paleochannels of Damodar fan-delta downstream of Barddhaman (after Niyogi 1975; Acharyya and Shah 2007) and **b** spatial extent of high magnitude floods (1959 and 1978) distributed through paleochannels to signify the potential area of getting silts and water (after Sen 1991)

previous capacity to accommodate flood water due to siltation. In the post-dam period when DVC dams suddenly had released excess water to save structure of dams, the floods were occurred in 1959, 1978, 1995, 1999, 2000, 2003, 2006, and 2007. Recently, due to heavy cyclonic rainfall (145 mm on 7 to 8.08.2011) over Jharkhand and Chhattisgarh from August 7, 2011, Tenughta, Panchet, and Maithon reservoirs released 454 $m^3\ s^{-1}$, 510 $m^3\ s^{-1}$, and 481 $m^3\ s^{-1}$, respectively. On August 8, 2011, that had a cumulative effect on Durgapur Barrage when 1,275 cumec water released through main channel and canals (Ghosh and Mistri 2013c). As a result on August 13, 2011, the numbers of total flood affected blocks of West Bengal were reached up to fifteen, and sixteen million people were directly affected from flood inundation (Ghosh and Mistri 2013c).

7.2 Decay of paleochannels

In the past, furious Damodar River (known as "*Sorrow of Bengal*") opened a number of distributaries or paleochannels (Fig. 15a), *e.g.,* Banka, Sapjala, Gangur, Behula, Ghea, Kana Damodar, etc., in Damodar fan-deltaic plain (Acharyya and Shah 2007; Ghsoh 2011). Now due to holding back of water in DVC reservoirs and diversion of water from the Durgapur barrage through left and right bank main canals for irrigation purpose, these paleochannels are gradually delinked and deteriorated since Rennel's time (1,783) till today (Ghsoh 2011). Constructions of sluices, canals, high embankments, roads, Eastern Railways, settlements, and intensive river bed agriculture have restricted the monsoonal flow in these channels and now they bear the previous signs as *Khals*, *Kana Nadi*, abandoned dry channel, and sinuous arrangement of ponds. But importantly these paths (if rejuvenated) can be served as major distributaries net of lower DRB in the time of floods as done in past to recharge surface and sub-surface water resources and to replenish the soils with silt (Fig. 15b).

The blocks of Memari I, Memari II, Bhatar, Pandua, etc. (situated in lower DRB) are facing the problem of declining ground water level. In recent periods, the monsoon rainfall (June–September) is not enough (while annual average 1,300–1,500 mm) for recharging ground water resource and storing adequate quantity of water in the upstream reservoirs to provide irrigation water (Ghsoh 2011). It forces the farmers to depend entirely on shallow tube wells and deep tube wells. Recent studies of Damodar floods reveal that as the frequent bankfull discharge and floods are more uncommon (due to burden of dams and embankments), the surface water bodies and ground water do not get ample quantity of monsoon flood water for long days. This problem is more aggravated with decaying of paleochannels and increasing population pressure.

The floodplain of lower DRB is made up of Chotangapur Plateau wash sediments (rich in minerals) carried down by the tributaries of Damodar which spread over this area as thick layer of clayey loam to silty loam soils with a reddish hue (Ghsoh 2011). With the control of repeated normal river floods, inevitably replenishing of new fertile alluvial soil has virtually been stopped.

8 Conclusion

The aforesaid analysis has brought into light new information about the influence of dams on Damodar River in relation to flood. The constructions of large dams create anthropogenic hindrances to maintain the previous natural entity and flood ferocity of Damodar River but the hydrogeomorphic processes are not radically altered at all, only its working magnitude is changed in respect of prescribed stimuli (external force). Due to loss of sufficient flow energy, the fluvial aggradation is more pronounced at downstream of Durgapur Barrage. It has been found that in few segments of lower Damodar River, the active channel bed is increased up to 2–3 meter from the adjoining floodplain. In post-dam era, the sinuous pattern (with confined meander) of Damodar River is achieved from downstream to upstream direction and the HSI is radically increased downstream compared to TSI. Braiding and avulsion are interlinked in the active floodplains in between Rhondia and Barddhaman, developing mature elongated islands and bars. The occurrences of clayey silt and silty clay on the top sedimentary facies of mature islands and banks reflect infrequent extreme flood events and low-magnitudes waning flood deposits in more sub-humid monsoon climate. FFMI of Damodar is increased due to high deviation of peak discharge from mean discharge in the monsoon period. Downstream of Borsul the Damodar River alters its active sinuous thalweg frequently in a confined meandering valley and changes its erosional and depositional processes subsequently in slip-off slope and cutoff slope, respectively. In between 1972 and 2006 (44 years), the adjoining lands of active floodplain are lost (averagely 0.12–2.23 km^2 at selected segments) due to bank erosion, which are more pronounced in between Palla and Paikpara. Alongside, the downstream channel capacity and bankfull discharges are gradually declined from 4,011 to 1,542 $m^3 s^{-1}$, reflecting high chances of overflow. The recurrence interval of this discharge ranges from 1.18 to 3.18 years only. If the annual flood series follows the trend of post-dam period, every 5-year flood or peak discharge will be greater than 5,300 $m^3 s^{-1}$ and 100-year flood will be above 11,000 $m^3 s^{-1}$. Constructions of sluices, canals, high embankments, roads, Eastern Railways, settlements, and intensive river bed agriculture have restricted the monsoonal flow, and the paleochannels are gradually delinked and deteriorated at present. This phenomenon has restricted the floodplain of Damodar to recharge groundwater and to get fresh silts occasionally.

After dam construction (more than 60 years), the channel capacity of Damodar must ultimately be governed by a balance between the erosive forces associated with high discharges and the aggradational processes together with vegetational growth associated with lower discharges. Depending on the locations of upstream reservoirs, the trapping of sediment, especially in monsoon region with prevalent soil erosion, frequently disturbs the fluvial system of Damodar, both upstream and downstream from the reservoirs. It is evident that the river becomes narrower and shallow as we go from Anderson weir toward Amta channel which carries maximum bankfull discharge of only 849 $m^3\ s^{-1}$. Up to Barsul, development of dunes, islands, and mature point bars and frequent shifts of thalweg reaffirm that the river are still adjusted with infrequent monsoonal flow and riverine anthropogenic activities, viz. river bed agriculture, embankment, and rigorous sand quarrying. It is a reality that after constructing DVC dams and associated structures, we do not control heavy inflow and overflow in lower DRB (trans-Damodar and Mundeswari area) in the time peak monsoon and cyclonic rainfall. The main problem is that the focus is in trying to control the river dynamics (strong natural force) in spate and not of making use of the flood water and sediment in the best possible way. We cannot expect long-term sustainability from the DVC dams and drainage system; the life spans of these structures are reduced gradually. It is the right time to think different and alternatives to use flood water employing modified drainage engineering and traditional knowledge. The main emphasis should be centered on the following sections: (1) managing sedimentation of reservoirs and river, (2) rejuvenating the paleochannels linked with five-years planning program and 100 days work, (3) linking these channels with Damodar River to maintain regular flow, (4) recharging surface and sub-surface water resources in monsoon, (5) improving drainage network (including canals) to disseminate flood water slowly to improve soil fertility, (6) delimiting flood risk zones and avoiding any type of construction within the active flood zone, (7) adapting with periodic inundation (precise flood forecasting and good number of flood shelters), and (8) alternative agricultural practices in lower DRB. Above all, the resources of a basin (mainly river) should be treated at first as ecological assets and then as economic assets. We cannot escape from the natural calamity, but we can effectively integrate the dams, embankments, river, agriculture, industry, and riparian communities to use flood water as a resource.

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