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ORIGINAL ARTICLE

Flood characteristics and dynamics of sediment environment during Anthropocene: experience of the lower Damodar river, India

Debasis Ghosh[1] · **Sambit Sheet**[1] · **Monali Banerjee**[1] · **Manas Karmakar**[1] · **Mrinal Mandal**[2]

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Abstract

Flood is considered as a very common natural disaster associated with the Indian rivers, and the lower Damodar river has been experiencing it since the long past. Heavy monsoonal rainfall during the short time period enhances the river flood which devastates mainly the lower part of the lower Damodar basin. The present study aims to analyse the past and present floods in the lower Damodar river using the recorded data and fluvial deposits, and also the societal interaction with these river floods. The entire work was carried out on the basis of a detailed field survey and secondary database. The recorded discharge data used in flood frequency analysis reveals 2 years of recurrence interval of flood during pre-dam condition; while in the phase of the post-dam situation, it was shifted to 10 years and 20 years recurrence interval at Rhondia gauge station and at the Damodar junction bridge site respectively. The mean grain size (M_z) of sediment distributed downstream ranges from 3.32ϕ to 1.19ϕ with significant variation in the downstream sorting process. This anomaly is due to high discharge events during the monsoon period and extensive unscientific sand mining during the lean period. The coarse and mixed grain sediment layers in the sediment succession of the lower Damodar river provide evidences of past flood events. In 2017, the lower part of the lower Damodar basin has experienced floods for 3–5 days, and more than 330,000 people along with many socio-economic and socio-cultural structures were severely affected. This study may help the concerned authority to take scientific steps for the necessary upgradation of the existing flood management systems to minimize flood vulnerability of the riparian society.

Keywords Damodar river · Grain size · Peak discharge · Recurrence interval · River flood · Sediment succession

Introduction

Flood is a natural phenomenon and its nature changes from place to place based on the anthropogenic intervention on and near the river. Floods remain the most common and devastating natural disaster (Mosquera-Machado and Ahmad 2007; Pradhan 2010; Ho and Umitsu 2011; Di Baldassarre et al. 2013; Bubeck et al. 2017; Das and Sahu 2017; Dano et al. 2019) causing large number of deaths, injuries, extensive damage of crops, infrastructures, properties, social life, etc. (Woube 1999; Doocy et al. 2013; IPCC 2007; Dewan 2015; Wilhelm et al. 2019; Tola and Shetty 2022). Globally, the flood-prone areas encompass about one-third of the total land area affecting almost 82% of the total population (Dilley et al. 2005), and every year, catastrophic floods occur in more than 90 countries on an average (UNDP 2004; Peduzzi 2006). During 1994–2013, floods are accounted for 43% of all occurred disasters affecting 2.3 billion people around the world (CRED 2015). The river flood occurs, when river

✉ Debasis Ghosh
dghoshcugeo@gmail.com

Sambit Sheet
sambit.sheet@gmail.com

Monali Banerjee
banerjeemonali2@gmail.com

Manas Karmakar
manaskarmakar206@gmail.com

Mrinal Mandal
mrinal8628@gmail.com

[1] Department of Geography, University of Calcutta, Kolkata, West Bengal 700019, India

[2] Department of Geography, Sidho-Kanho-Birsha University, Purulia, West Bengal 723104, India

water runs over its bank that is primarily induced by individual or combined act of some hydrological and meteorological factors (Watt 1989; Andrews 1993; Whitfield 2012). However, the characteristic of river flood is governed by the interaction among atmosphere, river catchments and river systems (Blöschl et al. 2015; Ciullo et al. 2017). The floods generally take place with varying rates of occurrence and magnitudes (Woo and Waylen 1986), which are considered to get influenced by several anthropogenic interferences within the natural river systems, such as construction of flood control measures, land-use changes and urbanization (Di Baldassarre et al. 2009; Ciullo et al. 2017). During the last three or four decades, the number of severe flood events has been increasing with higher intensity and magnitude in several places around the world as a result of climate change phenomena (Ferreira 2011; Khan et al. 2011; Nikolova and Nikolov 2011) which suggests that if the flood events are not properly managed, it will continue to increase in forthcoming years also (IPCC 2013; Blöschl et al. 2015; Kontgis et al. 2019). The Indian rivers that depend on monsoonal rainfall are very much associated with high magnitude floods (Kale 2005). The Indo-Gangetic Plains, drained by numerous monsoon-fed rivers are the world's worst flood-affected region, where destructive flood events occur almost every year (Agarwal and Narain 1996; Jain and Sinha 2003).

In recent times, the increasing trend of growth in population and settlements and the associated land-use changes within the close proximity of the river have amplified the human vulnerability to flood (Doocy et al. 2013; Kundzewicz et al. 2014; Tripathi et al. 2014; Dewan 2015; Karmokar and De 2020; Tola and Shetty 2022). To minimize this vulnerability, different flood defense infrastructures have been constructed in many flood-prone areas around the world (Castellarin et al. 2011; Ciullo et al. 2017). The change in the river hydrology is the result of human-river interactions within the river catchment and climate change, where human interventions contributed partially to the change (Vörösmarty et al. 2010; Lintern et al. 2016). Moreover, the sediments with varying properties deposited during the river discharge of different hydrological character can be used as evidences to identify the flood events that occurred in the past (Wolfe et al. 2006; Daesslé et al. 2009; Jone et al. 2010; Bábek et al. 2011; Ferrand et al. 2012; Lewin et al. 2017; Lintern et al. 2016; Wilhelm et al. 2019). Generally, the high discharge events bring and deposit coarser sediments downstream than the normal discharges (Toonen et al. 2017; Wilhelm et al. 2019), and therefore, the coarser sediment layer gives an indication of flood events (Chiverrell et al. 2019). In normal condition, the surface sediment of the river shows a downstream fining nature due to the deceasing stream power to carry coarser sediment towards downstream. However, during Anthropocene i.e. the present period of accelerated human interventions in the natural environment, the rivers have been experiencing exacerbated sand mining from the river bars, and these activities modify the sediment characteristics by mixing different grain sizes.

One of the frequently flooded rivers of Indo-Gangetic Plains is Damodar, and 80% of its annual discharge is caused by monsoonal rainfall (between June to September) (Mondal et al. 2018), and, therefore, the river exhibits a great tendency of flooding in its lower reach. There are some previous studies already conducted on Damodar river floods to perceive and assess the genesis of flood (Sen 1985), flood induced riverbank erosion (Sen 1991), the performance of dams in controlling flood (Bhattacharyya 1999), flood hydrology and flood frequency at Rhondia (Ghosh and Guchhait 2016), flood susceptibility mapping (Singh et al. 2020a, b, Singh et al. 2021a, b), etc. Studies already attempted by the previous researchers did not necessarily consider both the recorded data and fluvial sediments to conceive the nature of flood events and its interaction with society. The present study aims to analyze the nature of past and recent floods based on recorded data and fluvial deposits and societal relation to these floods in the lower Damodar basin (LDB). This study might be helpful for employing new and upgraded flood mitigation strategies in the study area.

Study area

The Damodar river, a tributary of the Bhagirathi-Hugli river system originates from the Khamarpat hill (~ 1068 m above msl) of the Chotanagpur plateau in Jharkhand and flows in an easterly direction through the major coalfields before meeting the Barakar river near Dishergarh. Then the river changes its direction to the south-east and finally after taking a sharp southerly bend, it bifurcates into the Kanki-Mundeswari and Amta channel just below Jamalpur in Barddhaman district of West Bengal and joins the Hugli river at ~ 48.3 km downstream of Kolkata, West Bengal, India (Bhattacharyya 1999). According to the Geological Survey of India (GSI), The upper and middle Damodar basin is composed of Chotanagpur Granite Gneissic Complex (CGGC) and Gondwana group of rocks (sandstone, grit, red clay/shale and Ferruginous sandstone), while the lower basin is largely consist of older and newer alluvium deposits. The general slope of the basin is towards south-east (Roy and Banerjee 1990), which varies from more than 70° in the upper catchment to less than 2° in the lower catchment. The Damodar river basin gets approximately 1200 mm average annual rainfall and the lower part of the basin receives more than 1370 mm rainfall annually of which 80% occurs during the monsoon season (India Meteorological Department 2018). In the present work, the LDB has been selected as the study area that extends from the confluence of the Damodar and the Barakar river to the downstream (Sen

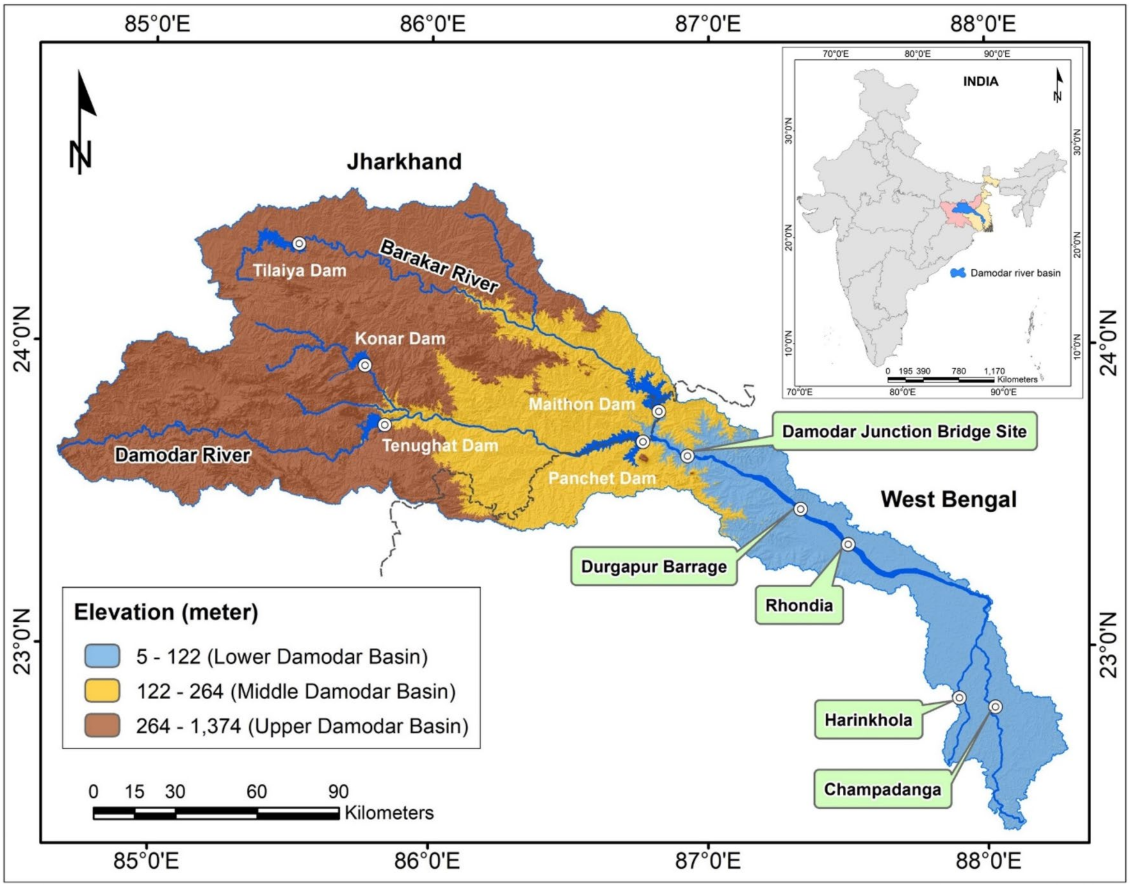


Fig. 1 Location map of the study area. The elevation of LDB located within West Bengal district ranges from 122 to 5 m. The white circles indicate the location of the dams, barrage and important gauging stations on the Damodar river system

1991) covering ~ 4915 km^2 area of Purulia Bankura, Barddhaman, Hooghly, and Howrah districts of West Bengal. The study area lies in between 23° 46′ N to 22° 23′ N and 86° 46′ E to 88° 16′ E with the elevation ranges from 122 to 5 m (Fig. 1). The downstream areas of LDB have experience severe and frequent flood events since long past. To moderate the floods, till date three upper dams namely Tilaiya (1953), Konar (1955), Tenughat (1978) and two lower dams and one barrage explicitly Maithon (1957), Panchet (1959), and Durgapur barrage (1955) have been constructed on the Damodar river system (Chandra 2003) (Fig. 1). The flood events have developed extensive fertile floodplain area mainly in the lower part of LDB which is densely occupied by more than 20 lakh population (Census of India 2011).

Materials and methods

Data set

The data used in this study were acquired through a detailed field survey and from different government offices and official websites. Version 3 of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 1 arc-sec (30 m spatial resolution) was downloaded from Earth Explorer Interface (https://earthexplorer.usgs.gov/) developed by the United States Geological Survey (USGS) to prepare the base map of the study area. And to do the same, Topographical maps of Survey of India (73 M/7, M/11, M/12, M/15, M/16, N/13, N/14 and 79 A/4, B/1, B/2) with a scale of 1:50,000 were also employed. Yearly 1-day peak discharge volume for long period of time were collected from the Hydraulic Data Division, Damodar Valley Corporation (DVC), Maithon and Bhattacharyya (2011). The data of the last major flood event in 2017 at the lower part of the study area were obtained from Irrigation & Waterways Department, Kolkata, Govt. of West Bengal and Irrigation and Waterways Directorate, Champadanga, Hooghly. During the field survey, sediment samples were collected from the transverse phase of each trench considering the entire unit across the inclined lamina, cross lamina, cross bedding and/or parallel bedding and also from sediment succession by using metallic pipe and stored in the container. Cross-sectional data of the studied river reach were generated in the field by employing Total Station (Make-Geomax, Model-ZT 20). Condition of riverine villages in the lower part of the LDB during the 2017 flood was assessed through field visits at that time. The Google Earth Pro software (version 7.3) is used to acquire the location of dams, barrage, gauging station, flood-affected villages and to quantify anthropogenic activities existing within the study area.

The base map of the study area was generated with the help of SRTM DEM and Topographical maps by employing the Hydrology toolset in ArcGIS 10.3.1 software. Particle size analysis of collected sediment samples is performed through the sieving process after drying the samples in a hot air oven. Thereafter, the measurements of all statistical parameters of sediment grain size are done applying the logarithmic formulae of Folk and Ward (1957) in G-Stat 2.3 software. The parameters are represented graphically as bar graphs using Golden software Grapher 9. SedLog 3.1 and Corel DRAW 12 software were used to prepare sediment stratigraphy from the sediment succession data of the river. MS-Excel is also used to represent the daily discharge data and gauge height data recorded at different gauging stations during the last major flood event in 2017.

Flood frequency analysis (FFA)

The data of yearly 1-day peak discharge volume were arranged in MS-Excel and represented as a line graph. These data were also used for Flood Frequency Analysis (FFA) by using three different models: In the Weibull's probability distribution model known as Weibull's Plotting Position, the collected 1-day peak discharge data were ranked after arranging it in a general descending order, and the largest discharge is assigned a rank of one ($m=1$) and the next highest discharge is given rank two ($m=2$) and so on (Pal 1998). According to this method, the 'return period' or 'recurrence interval' (T) in years is computed as:

$$T = (N + 1)/m, \tag{1}$$

where, 'T' = recurrence interval or return period, 'N' = period of the recorded data series, i.e. sample size, and 'm' = rank of discharge events.

Hence, the 'probability' (p) and 'percent probability' of occurrence of a particular peak discharge or flood of the recorded series is calculated by the following formulae:

$$p = m/(N + 1), \tag{2}$$

$$\text{Percent probablity} = (p * 100)\%. \tag{3}$$

The extreme value distribution model, introduced by Gumbel (1941) is used most extensively to predict extreme values of different weather phenomena like flood peaks (Subramanya 2008). The general equation to predict the value of 'x' variate (discharge) with a selected recurrence interval 'T' given by Gumbel is used as:

$$x_T = \overline{x} + K \cdot \sigma, \tag{4}$$

where '$\overline{x}$' is the mean peak discharge or flood, 'σ' is the standard deviation of peak discharge or flood, and 'K' is the frequency factor, expressed as:

$$K = \frac{y_T - \overline{y}_n}{S_n}. \tag{5}$$

In which, 'y_T' is the reduced variate, a function of 'T' and is given by:

$$y_T = -\ln\left[\ln\frac{T}{(T-1)}\right]. \tag{6}$$

And '$\overline{y_n}$' is the reduced mean, a function of sample size 'N'; for 'N' = ∞, '$\overline{y_n}$' is 0.577.

'S_n' is the reduced standard deviation, a function of sample size 'N' and is given in Appendix Table; for $N=\infty$, 'S_n' is 1.2825.

In the Log-Pearson Type III distribution model, the data of peak discharge series ('x' variate) are first converted into logarithmic forms ('Z' variates) and then the analytical procedure starts.

$$Z = \log x. \tag{7}$$

This 'Z' series is used to predict the value of 'Z' variate for any selected return period (T) by applying the following formula:

$$Z_T = \overline{Z} + k_Z.\sigma_Z, \tag{8}$$

where, '$\overline{Z}$' is the mean of 'Z' variates, 'σ_Z' is the standard deviation of 'Z' variates, and 'K_z'is a frequency factor which is a function of the return period (T) and skew co-efficient (C_s) of 'Z' variates.

$$\text{Skew co - efficient}(C_s) = \frac{N\sum(Z-\overline{Z})^3}{(N-1)(N-2)(\sigma_Z)^3}, \tag{9}$$

where 'N' is the number of years of record.

After finding 'Z_T', the corresponding value of 'x_T' (discharge) is obtained by the equation given below:

$$x_T = \text{antilog}\left(Z_T\right). \tag{10}$$

The whole methodology can be summarized as the hydrological data related to the flood have been analyzed by using three statistical models to concretize the results and predictions to fulfil the objectives concretely with numerical evidences. The sediment samples have been analyzed mainly by following Folk and Word method. The stratigraphies have been analyzed using different graphical techniques. These techniques have been used to represent the results lucidly and tried to generate concrete evidences in support of the result's interpretations.

Results

Nature of flood

Peak discharge characteristics: Damodar junction bridge site (DJBS)

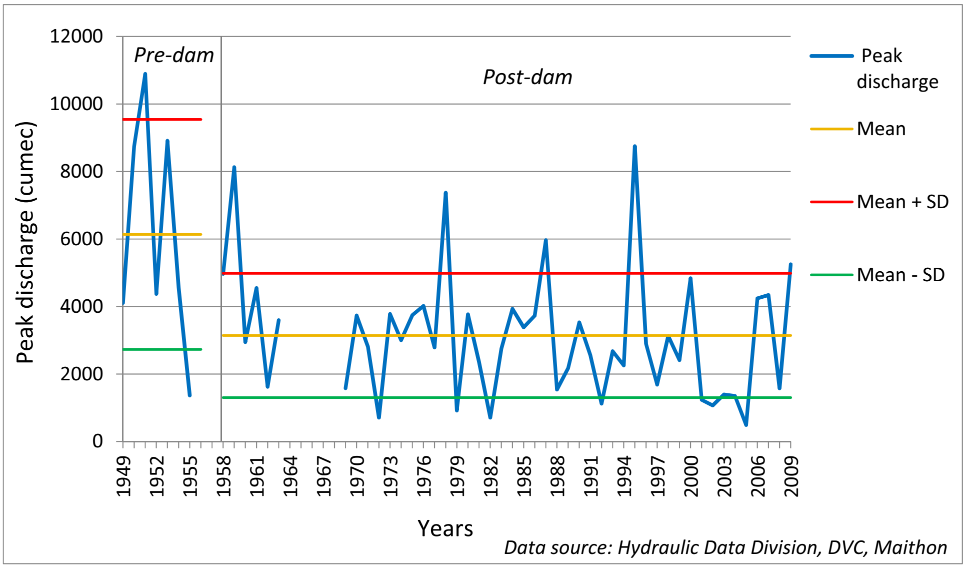
At DJBS gauging point continuous discharge are available for 1949–2009 with the missing year of 1956, 1957, and 1964–1968. The available daily discharge data categories into two seasons: pre-dam period (1949–1955) and post-dam period (1958–2009) to understand the peak discharge conditions in case of natural and controlled river conditions dividing into two seasons (Fig. 2). The highest 1-day peak discharge at this gauging station during the pre-dam period was 10,892.06 cumec in the year 1951 and during the post-dam period was 8750 cumec in the year 1995. The mean annual 1-day peak discharge was recorded as 6134.95 cumec in the pre-dam period and 3141.39 cumec in the post-dam period.

Peak discharge characteristics: Rhondia gauge station (RGS)

At RGS site the daily peak discharge data is continuously available from 1932 to 2007, which have been divided into two seasons: pre-dam (1932–1957) and post-dam (1958–2007) for a better understanding of hydrological characteristics (Fig. 3). The highest 1-day peak discharge at this gauging station during the pre-dam period was 18,123 cumec in the year 1935, and during the post-dam period it was recorded as 10,919 cumec in 1978. The mean annual 1-day peak discharge of Lower Damodar River (LDR) at this gauging station was measured as 8099.65 cumec in the pre-dam period and 3598.28 cumec in the post dam period.

Flood frequency analysis

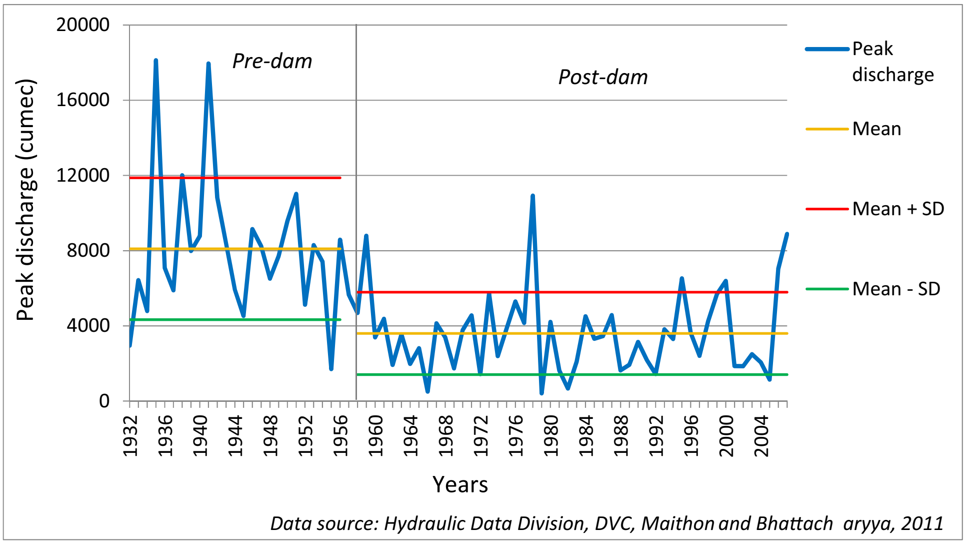
Flood frequency analysis at Damodar junction bridge site (post-dam period) Before 1969 at DJBS gauging station continuous annual daily peak discharge data is unavailable which is confined to the results of flood probability analysis during pre-dam situation and post dam period that leads to a limit to the forecasting of the flood. The analysis done using Weibull's plotting position model revealed that the recurrence interval of the higher 1-day peak discharges such as 8750 cumec in 1995, and 7372.63 cumec in 1978 are 42 years, and 21 years respectively with a corresponding probability of occurrence of 2.38% and 4.76%. The lowest 1-day peak discharge that was recorded as 488.50 cumec in 2005 has a return period of ~ 1 year with 97.62% probability of occurrence (Fig. 4a). Gumbel's extreme value distribution model estimated that at this site the probable discharge for the lower return period like 2 years and 5 years are 2689.94 cumec and 4442.54 cumec, respectively, while for the higher return periods, such as 50 years, 100 years and 200 years are 8156.71 cumec, 9236.34 cumec and 10,312.04 cumec, respectively (Fig. 5). In the case of Log-Pearson Type III probability distribution model, it has been calculated that the expected discharge for return periods of 2 years and 10 years are 2600.52 cumec and 5438.17 cumec, respectively, and for 50 years, 100 years, and 200 years return periods are 7835.98 cumec, 8798.91 cumec and



Data source: Hydraulic Data Division, DVC, Maithon

Fig. 2 Variation in annual 1-day peak discharge during pre-dam and post-dam period at DJBS. Three highest peaks of discharge are observed in a time span of 18–20 years from each other, which clear from the post-dam data

Fig. 3 Variation in annual 1-day peak discharge during pre-dam and post-dam period at RGS

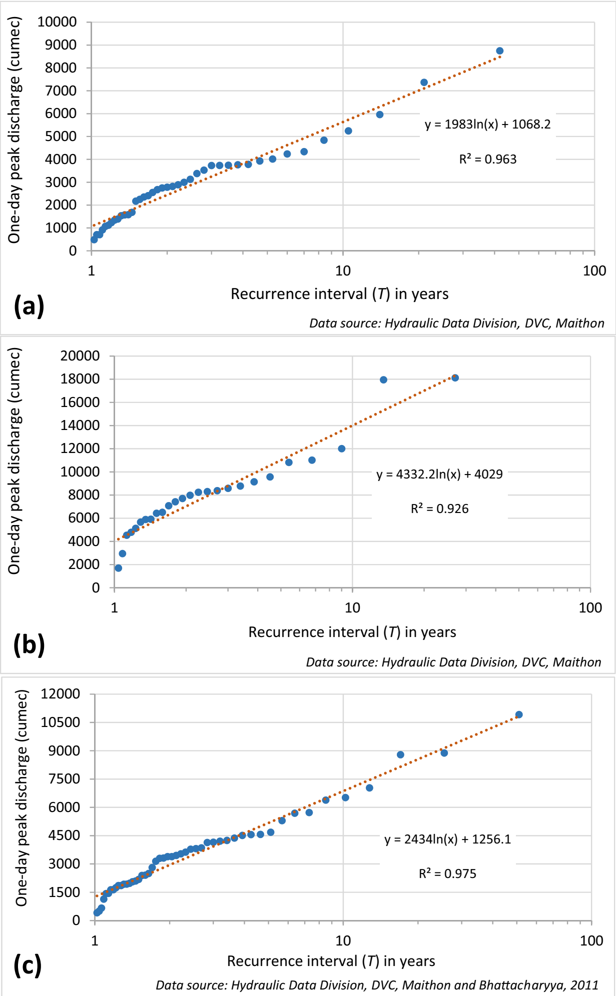


Data source: Hydraulic Data Division, DVC, Maithon and Bhattach aryya, 2011

9720.63 cumec, respectively (Fig. 6). The values of probable discharge at this site as given by three different methods shows very little contrast among them.

Flood frequency analysis at Rhondia gauge station (pre-dam period) At RGS site by plotting the results of daily peak discharge analysis of pre-dam data using Webell's method revealed that the recurrence interval of daily peak discharge in 18,123 cumec in 1937 in 27 years with 3.7% probability of occurrences. One-day peak discharges, like 17,953 cumec in 1941, 12,006 cumec in 1938, 11,015 cumec in 1951 had attained the return period of ~ 14 years, 9 years, and ~ 7 years with a probability of occurrence of 7.41%, 11.11%, and 14.81%, respectively. The return period of the lowest 1-day peak discharge in this series i.e. 1699 cumec in 1955 is calculated as ~ 1 year with the probability of 96.30% (Fig. 4b). The analysis by Gumbel's extreme value distribution model shows that during pre-dam period, the expected discharge for the lower return periods, such as 2 years and 5 years were 7530.36 cumec and 11,429.49 cumec, respectively, which increases to 19,692.66 cumec, 22,094.59 cumec and 24,487.76 cumec for 50 years, 100 years, and 200 years return period, respectively (Fig. 5). As compared to Gumbel's extreme value distribution, Log-Pearson Type III distribution model predicted lower discharge values except for the predicted discharge of 2 years return period. According to this model, during pre-dam period, probable discharge at RGS for a return period of 2 years and 10 years were 7772.11 cumec and 12,962.61 cumec, respectively, while the probable discharge for 50 years, 100 years and 200 years return periods were 16,114.83 cumec, 17,159.77cumec and 18,065.73 cumec, respectively (Fig. 6).

Flood frequency analysis at Rhondia gauge station (post-dam period) Weibull's plotting position model pre-



Data source: Hydraulic Data Division, DVC, Maithon

Data source: Hydraulic Data Division, DVC, Maithon

Data source: Hydraulic Data Division, DVC, Maithon and Bhattacharyya, 2011

Fig. 4 Weibull's probability of flood frequency in LDR **a** at DJBS (post-dam period), **b** at RGS (pre-dam period), **c** at RGS (post-dam period)

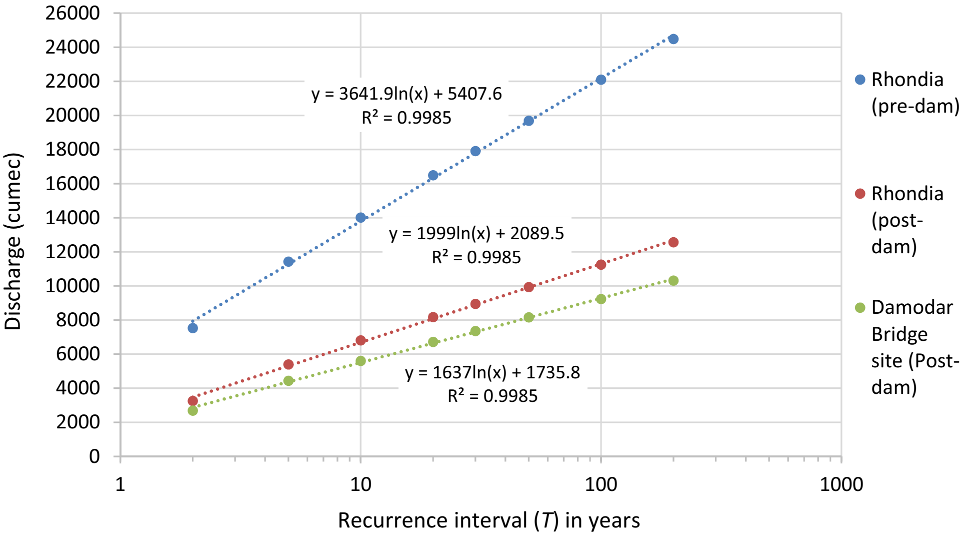


Fig. 5 Gumbel's extreme value distribution of flood frequency in LDR at DJBS (post-dam period) and at RGS (pre-dam and post-dam period)

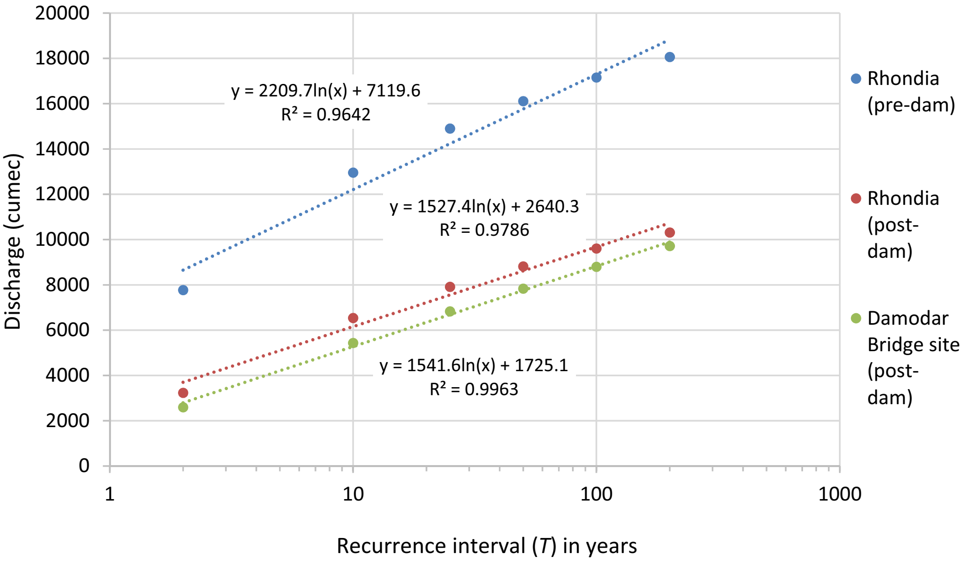


Fig. 6 Log-Pearson Type III distribution of flood frequency in LDR at DJBS (post-dam period) and at RGS (pre-dam and post-dam period)

dicted that 1-day peak discharge of 10,919 cumec in 1978 has a return period of 51 years with 1.96% probability of occurrence in post-dam period. While the return period of the lowest 1-day peak discharge in this series i.e. 413 cumec in 1979 is calculated as ~ 1 year with the probability of 98.04%, the 1-day peak discharges like 8883 cumec in 2007 and 8792 cumec in 1959 have attained the return period of ~ 26 years and 17 years with a probability of occurrence of 3.92% and 5.88% respectively (Fig. 4c). The discharges predicted by Gumbel's extreme value distribution model for the return period of 2 years and 5 years are 3254.64 cumec and 5394.85 cumec respectively, and for 50 years, 100 years, and 200 years are 9930.47 cumec, 11,248.88 cumec, and 12,562.48 cumec respectively in the post-dam period (Fig. 5). The probable discharge values for all the return periods as calculated using the Log-Pearson Type III distribution model are lower than Gumbel's distribution. The predicted discharge for a return period of 2 years and 10 years are 3237.42 cumec and 6537.39 cumec respectively, which increases to 8816.16 cumec, 9610.95 cumec and 10,314.87 cumec for 50 years, 100 years, and 200 years return period respectively (Fig. 6).

Surface sediment character of the river

To identify the grain size characteristics along with its distribution within the studied reach of river Damodar are total 32 sediment samples have been collected and analyzed, from where the downstream variation of grain size have been clearly revealed the mean grain size (M_z) is varying from 3.32ϕ to 1.19ϕ (Fig. 7). It indicates that medium to fine grain sand is dominant in this region. Among all sediment

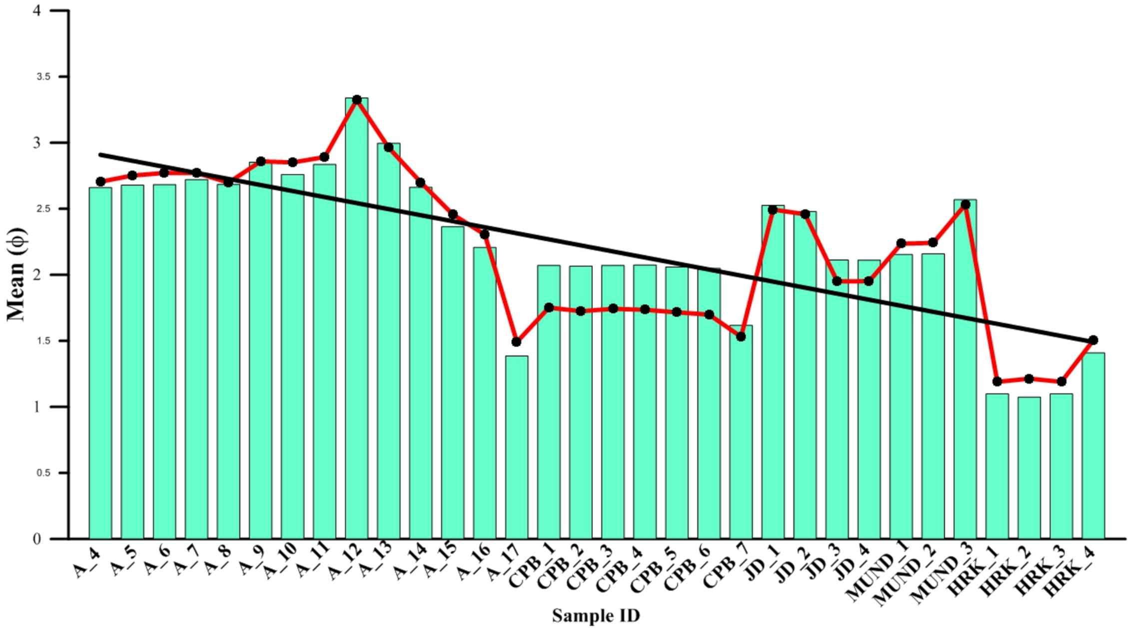


Fig. 7 Mean grain size of the sediment samples collected from the different sites of LDR. The samples are collected from upper LDR to lower LDR. Mean grain size of sediment samples are decrease towards downstream

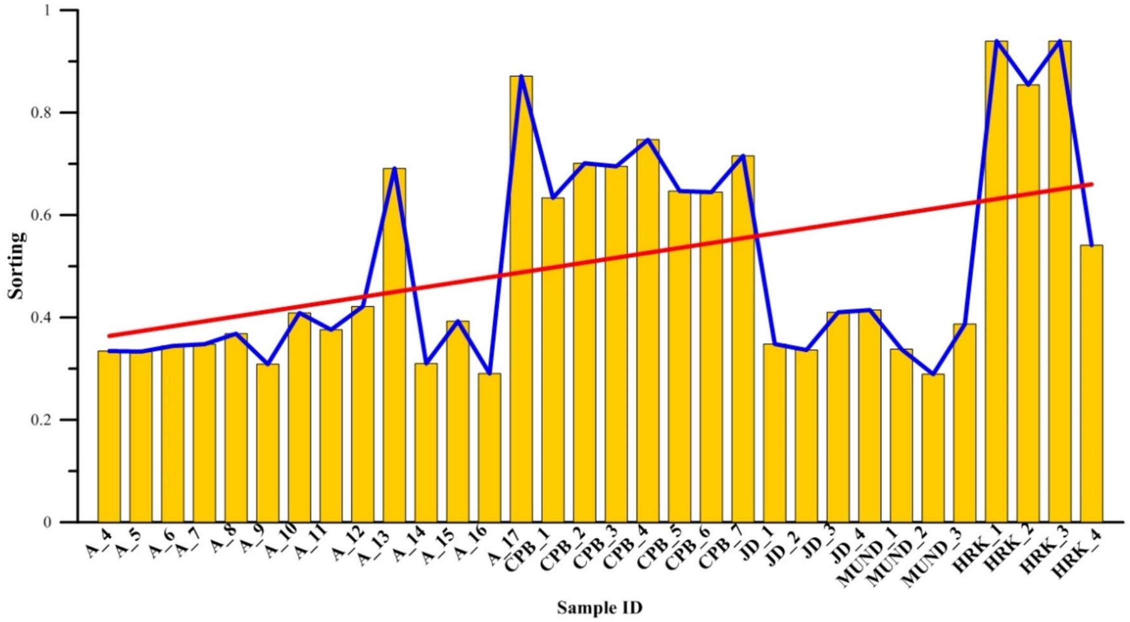


Fig. 8 Sorting of the sediment samples collected from the different sites of LDR. The sediment shorting analysis within the studied reach in LDR clearly revealed that 40.63% samples are moderately to moderately well shorted and 59.37% are well to very well shorted on the other hand

samples, 43.75% samples belong to medium sand and 56.25% samples exhibit fine to very fine sand. The sediment shorting analysis within the studied reach in LDR clearly revealed that 40.63% samples are moderately to moderately well shorted in one hand while 59.37% are well to very well shorted on the other hand (Fig. 8). Skewness depicts the asymmetric distribution of grain size in the studied river reach, where 71.88% samples are asymmetrical and 28.12% samples are symmetrical. Of analysed sediment samples, 46.88% samples are extremely-leptokurtic to leptokurtic in nature, while 53.12% samples are mesokurtic to platykurtic. In general, highly well-sorted sediment sample tends to be leptokurtic, which is expected in the studied reach. But in the present study, grain size analysis shows that the numbers of leptokurtic samples are less than well-sorted samples. The results of the sediment analysis in the case of LDR clearly signify that the flood events along with the anthropogenic interventions basically modify the sediment entrainment processes along with the fluvial regimes.

Discussions

The shape of the Damodar river basin is like a tadpole, which has a deep impact on its flow pattern along with the fluvial regime. Another relevant information that is important to mention here, that the upper catchment of the Damodar river is composed of the rock of CGGC, which contributes rapid and sharp surface runoff to the channel. On the other hand, the lower part of the catchment comprised of compact alluvium with heavy moisture condition that leads to favourable condition for getting flooded. During the heavy downpour in the upper catchment areas of the river, automatically creates a huge pressure of discharge in its lower basin areas after certain time of collection of the surface run off and the combined flow wants to be passed on through the chicken neck of its lower-most segment. But high energetic flow exceeds the capacity of the river channel that overtops the banks and ultimately has given rise to create flood condition in the lower part of the river. An interesting feature of this basin is that both upper and lower catchment does not use to receive the same amount of rainfall during the monsoon. The inundation of the lower reach may not all the time because of high rainfall condition, rather the region gets flooded due to the release of dam water from the upper catchment.

The pattern of 1-day peak discharge in different gauging stations signifies that there is a sharp contrast between pre-dam and post-dam period. According to the report of the Committee for the Augmentation of Water Resources of DVC (DVC 1959), a discharge of 7079 cumec (250,000 cusec) at Durgapur may be regarded as safe, but to avoid flood incidents this should not be exceeded. It is clear that the magnitude of the peak discharge has been lowered significantly in the post-dam period which is due to the flood controlling measures in the form of large dams, barrage, etc. Considering all the three models (Figs. 4, 5, 6), it is revealed that in pre-dam condition, the recurrence interval of the flood was 2 years, whereas, during post dam period, the recurrence interval is modified to 10 years at RGS and 20 years at DJBS. Interestingly, during the last 30 years, the studied region experienced a disastrous flood in 1995, 2007 and 2017 at an interval of almost 10 years. It is also noted that the occurrences of high magnitude floods are greatly lowered by the dams and barrage constructed on it, but the region often flooded without any pattern because of the release of dam water.

In the present study, sediment analysis reveals the anomaly in the mean grain size of the sediment with a downstream variation. In the studied river reach, medium grain size more specifically the gravely sand (Fig. 9) is quite abnormal according to sediment gradient law because grain size continuously decreases towards downstream. Anomaly in grain size distribution occurs due to both natural condition and anthropogenic interventions. In Damodar, high discharge events take place during monsoon time and the sediment entrainment processes gets resuscitated intensely. It is also mentioned that during flood time, many anthropogenic structures were destructed and carried through the streamflow and often get deposited within sediment bedding. During the lean period, extensive unscientific sand mining from the river bed (Fig. 10e) disrupts the sediment environment of this region and is responsible for the uncertain distribution of sediments. Presently, within the total stretch of the LDR, ~ 67 km^2 area of the point bar and mid-channel bar is seriously affected by sand mining (Fig. 11). Excavated mining pit in the lower reach of a river creates a local knick point in the longitudinal profile of the river. By the process, increasing the steepness of the channel slope increases the energy of the flow and is responsible for the accumulation of medium grain sand in LDR. The sand mining operates in two forms, namely, bar skimming and pit excavation. These processes ultimately have given rise to the modifications of river cross-sectional area along with its flow regime. Bar skimming due to sand mining leads to the increase of flow width and pit excavation increases flow depth. By comparing two cross sections of 2013 and 2019 (Fig. 12), it is clearly observed the intensity of extraction of sand and modification of cross-sectional area. Sediment free stream flow beyond the site of excavation picks up more sediments causing further degradation of the river bed.

The hydrological character of LDR is totally dam-controlled and it experiences high discharge events only during the monsoon period due to the larger upper catchment area and low discharge during the lean period. These seasonal changes in river discharge, sand mining activities and other anthropogenic interventions are responsible for changing hydrological regime and anomaly in the downstream variation of sediment properties (Figs. 7, 8, 9).

Sediment sequence used to give paleo-environmental clues which preserved as an archive for the reconstruction of the processes operated in the studied segment. It has given the information about changing flow regimes, sediment entrainment processes and details of fluvial depositional patterns of the LDR. Two sediment successions have been studied in the lower reach of Damodar. One from the right bank, having a trench depth of 1.78 m [near Chalbalpur

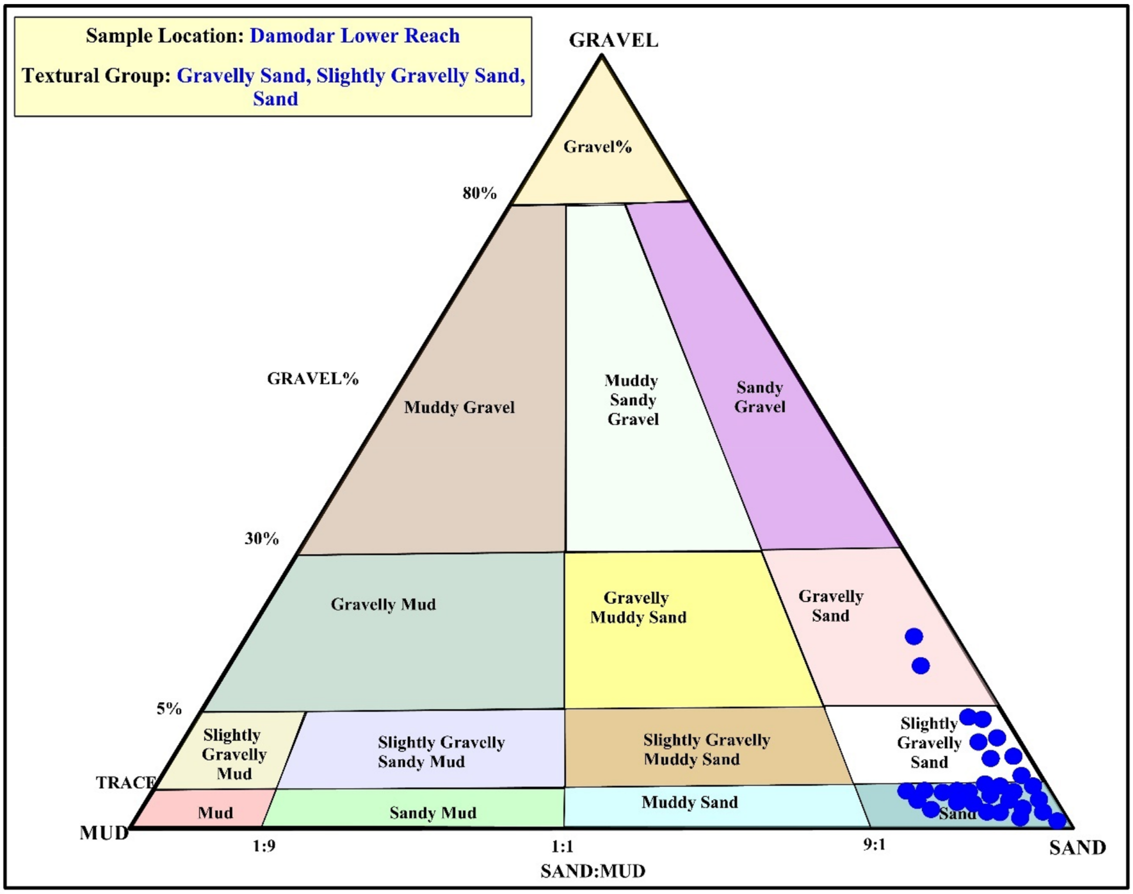


Fig. 9 Textural group of the collected sediment samples from the lower reach of the Damodar river. Most of the samples displayed the textural character of sand, while 28.13% samples belong to the textural group of gravelly to slightly gravelly sand

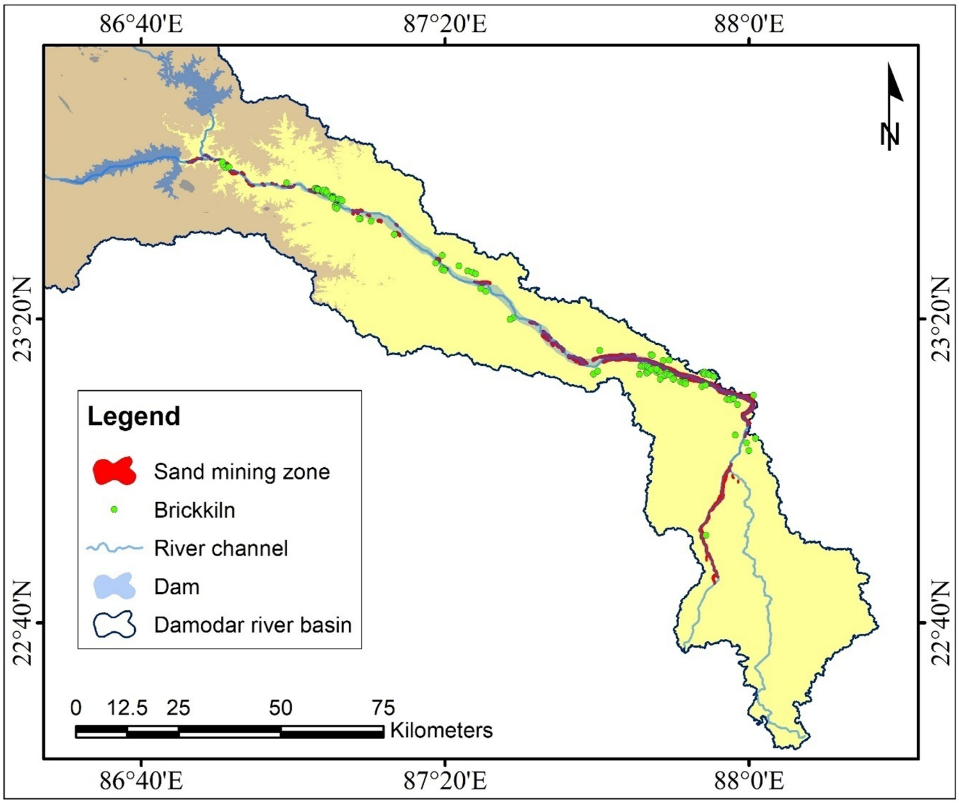
village of Jamalpur Community Development (C.D.) block] (Fig. 13), and the other studied from the left bank with a depth of 2 m near Taherpur village of Galsi-II C.D. block (Fig. 14). The right bank and the left bank stratigraphy have 13 and 17 successive beds respectively, which are characterized by alternative deposition of different beds of fine grain, coarse grain, mixed grain sediment and mud layer with different widths and orientations (Fig. 10a). These layers confirm the changes in flow velocities and hydrological regimes in different periods of the past. The coarse grain bedding in between the fine-grain layers indicates the high discharge events like flood, while the fine-grain layers depict the low or normal discharge events.

In the left bank stratigraphy, the deposition of poorly sorted mixed grain layer near the top (Fig. 14) is a prime evidence of the flooding event when sediment of different grain sizes is transported and deposited downstream. This poorly sorted sediment also includes the fragments of concretes, bricks, etc., which were transported through floodwater after the collapsing of anthropogenic structures by floodwater flow. The mud layers in the stratigraphy is an evidence of the ponding effect and very low discharge during the lean period when the suspended load of the river water had enough time to settle down above the deposited sand and the mud cracks can be seen during the dry period in many places downstream (Fig. 10b).

The flood events have been experienced by the riverine society since its inception. The people gradually used to live and adopted the art of living with the flood. There was a long history of regular flooding of the lower Damodar reach and the river became famous as “Sorrow of Bengal”. Due to the availability of fertile soil and other riverine resources in the floodplains of LDR, people started to live very close to the river, and the number of households and population density also have increased. But in the past few decades, the capacity of the reservoirs mainly of Maithon and Panchet dams are lowered due to the high rate of siltation (Chettri and Bowonder 1983). Therefore, the dams started to release a large amount of water during the high monsoon rainfall. The huge amount of released water could not able to accommodate by the channel and exit through the chicken neck type of the basin within a very short period of time made

Fig. 10 **a** Sediment succession of LDR at its right bank near Chalbalpur village containing distinctive layers with varying grain sizes and orientations of deposited sediments, **b** mud cracks developed due to ponding situation during the dry period on the point bar of the LDR, **c** Rhondia weir also known as Anderson weir **d** inaugurated on the LDR by Sir John Anderson in 1933, **e** extraction of sand from the point bars of the LDR, **f** newly constructed house types in the floodplain areas of the LDB to minimize the vulnerability to flood

Fig. 11 Location of sand mining zone and brickkilns within the LDR and its basin area



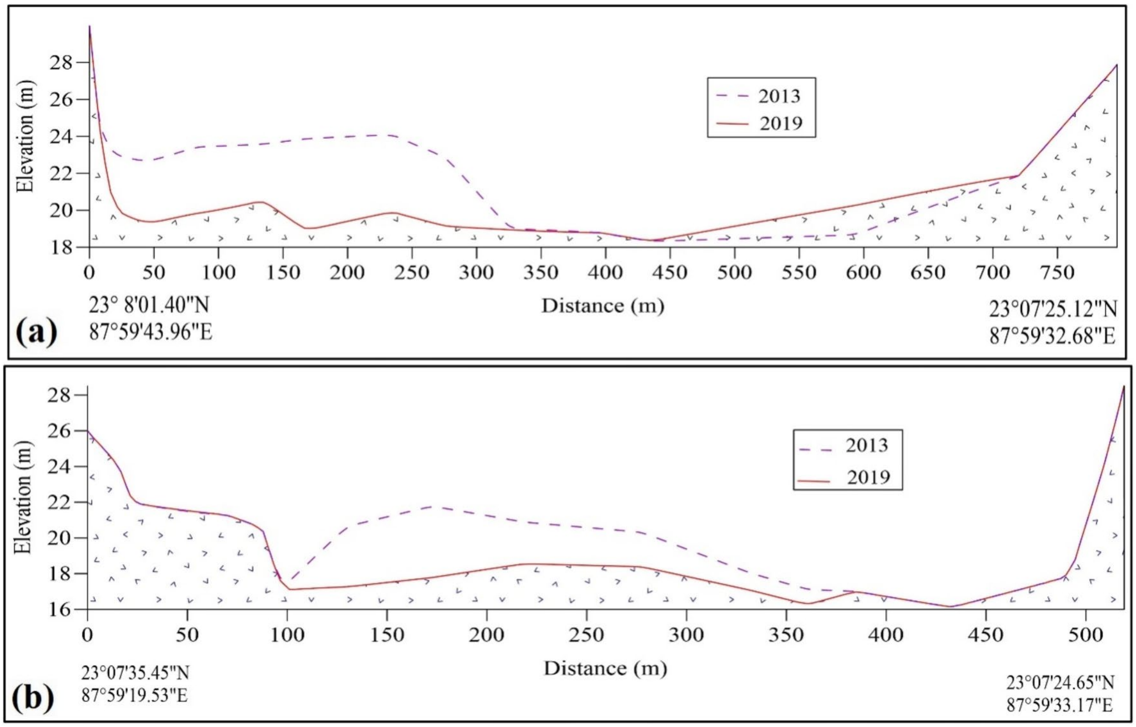


Fig. 12 Cross-sections at **a** Chalbalpur segment and **b** Sadipur segment of the LDR in 2013 and 2019. The lowering of river profiles from 2013 level indicating destruction of sand bar due to sand mining activities. About 70% and 55% of the point bars have been removed at Chalbalpur and Sadipur segment respectively

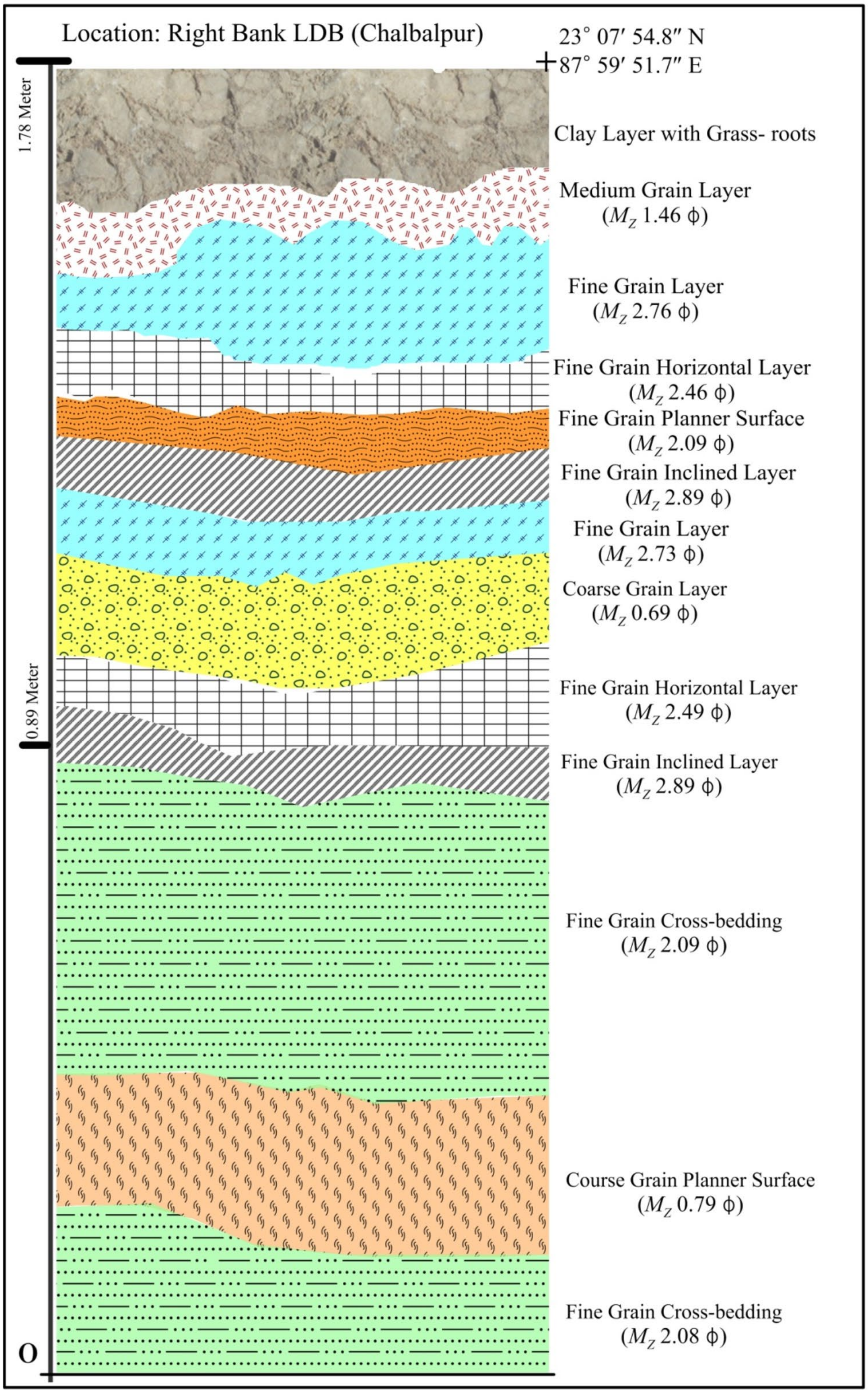
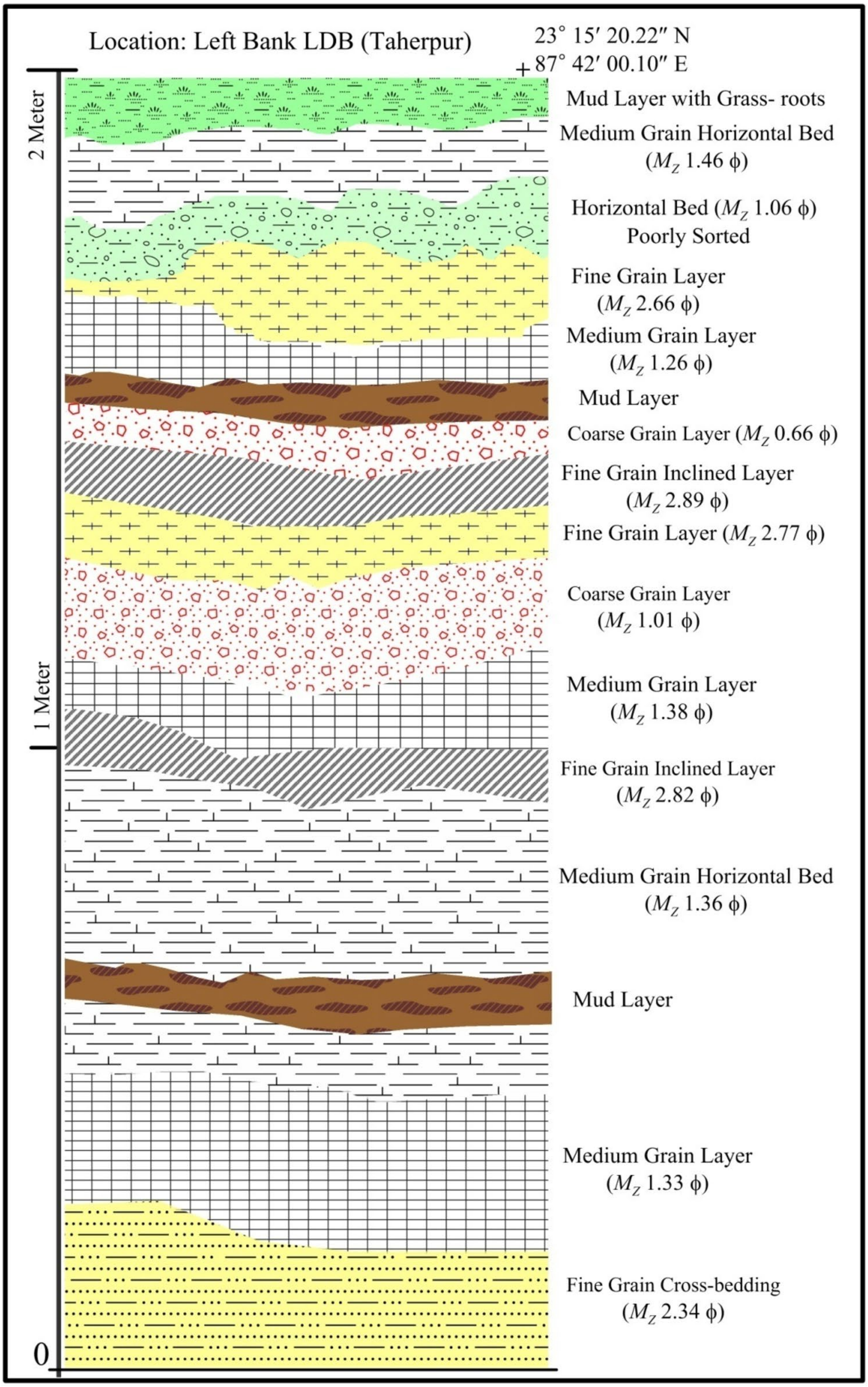
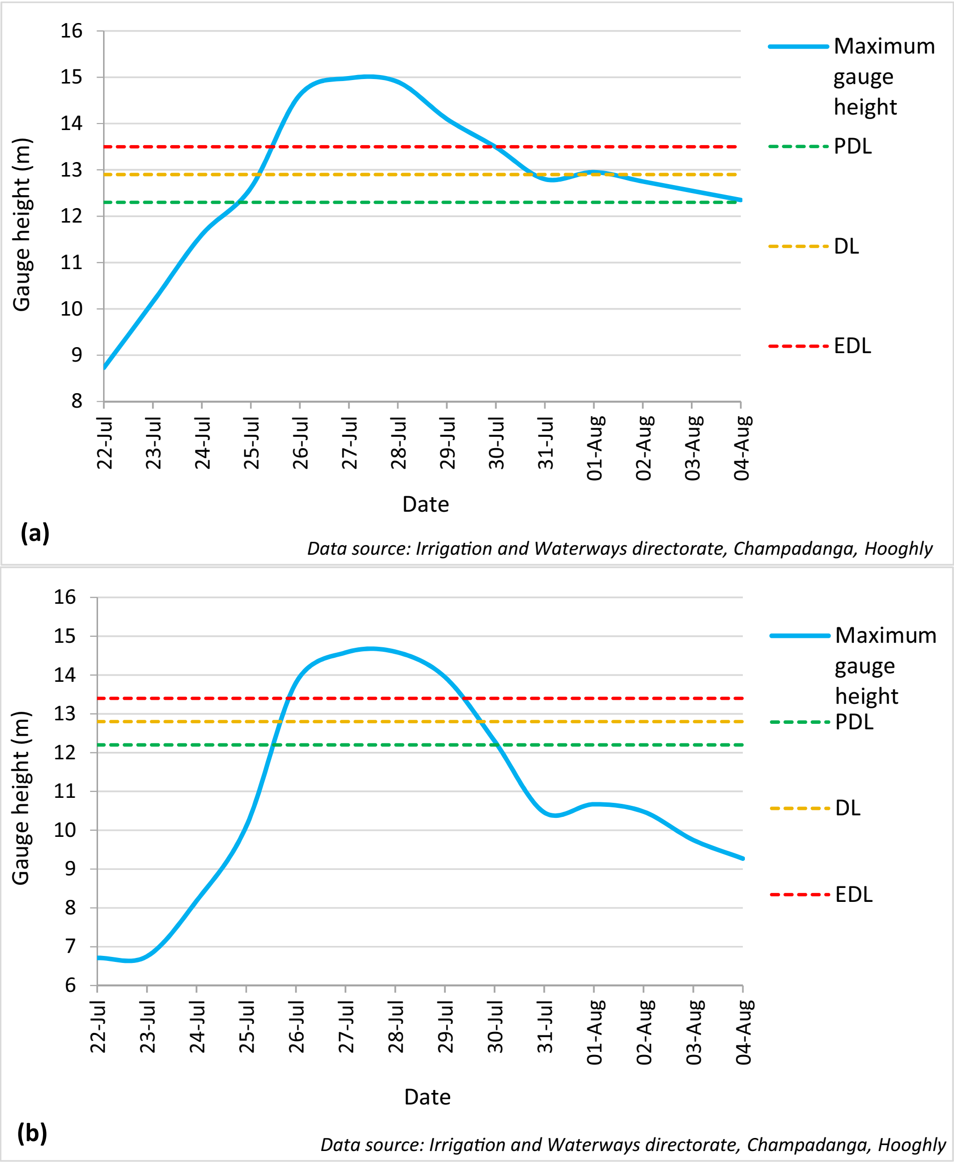


Fig. 13 Sediment succession with grain size and bedding characteristics of each layer of the LDR at its right bank near Chalbalpur village

Fig. 14 Sediment succession with grain size and bedding characteristics of each layer of the LDR at its left bank near Taherpur village





Data source: Irrigation and Waterways directorate, Champadanga, Hooghly

Data source: Irrigation and Waterways directorate, Champadanga, Hooghly

Fig. 15 Maximum gauge height and different danger levels of flow at **a** Champadanga gauge station of Damodar river, where gauge height is above the extreme danger level continuously 4 days **b** Harinkhola gauge station of Mundeswari river during 22nd July to 4th August in 2017. During 26th July to 29th July gauge height is above the extreme danger level

the situation most aggravated and vulnerable for flooding in its lower reach.

Flood in 2017 and its impact on riparian villages

During late July to early august 2017, the upper catchment area had received cats and dog rainfall and was measured at the gauging station of Maithon, Panchet, Asansol ad Durgapur. The effect of that received rainfall clearly reflected through the major flood in the LDR part mainly in the month of July 2017 with a departure of rainfall from the normal ranged from + 74.87% to + 154.20% up to Durgapur and + 43% departure at Burdwan gauging station. Durgapur barrage released more than 5000 cumec water into the river channel on the study July. The last major flood event in the LDR occurred between late July to early August of 2017. The upper catchment area received a huge amount of rainfall along with the rain gauge stations of Maithon, Panchet, Asansol, and Durgapur in the month of July 2017. The departures of rainfall from the normal were ranged from + 74.87 to + 154.20% at the aforesaid rain gauge stations. The rain gauge station at Burdwan also had experienced + 43% departure of rainfall from the normal. From Durgapur barrage 5000 cumec water released for 26th July as a consequence the gauge height of the river exceed stheir normal and average to an extreme danger level in case of all LDR gauging station like Chapadanga on Damodar and Harinkhola in Mundeswar (Fig. 15a, b). Furthermore, to maintain the safe reservoir water level, on 27th July combined discharge of Maithon and Panchet dams exceeded the combined inflow and consequently, it exerted more pressure on the Durgapur barrage which compelled to release huge

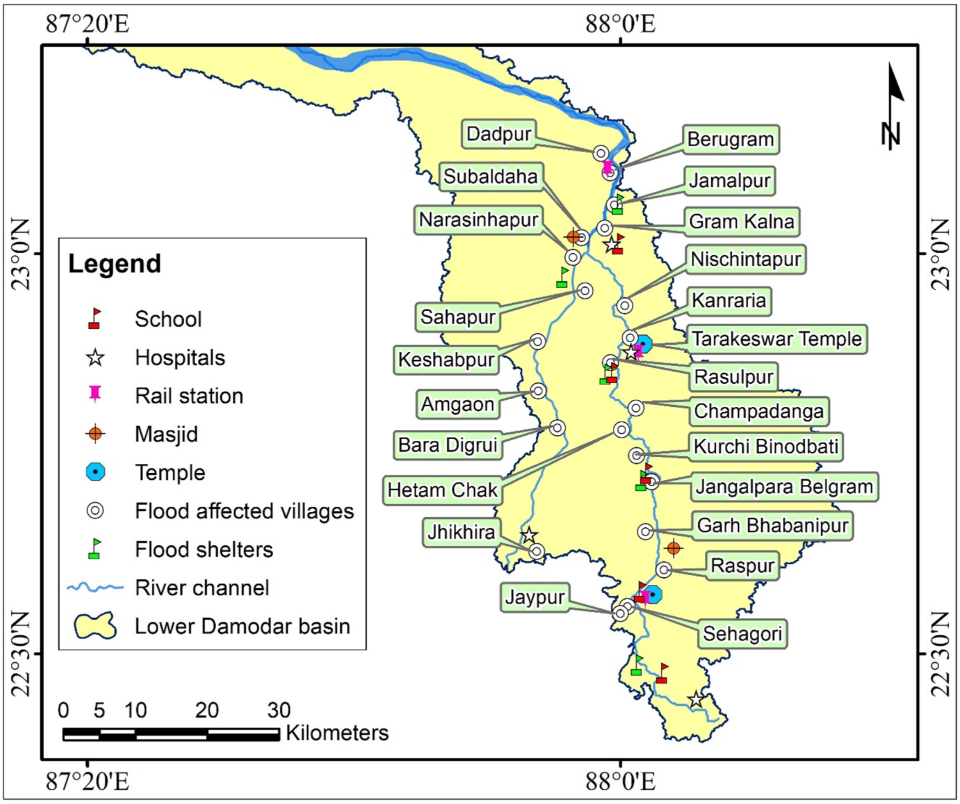


Fig. 16 Location of some severely flood affected villages, socio-economic and socio-cultural structures along with the flood shelters located in the lower part of LDB

volumes of water (> 7000 cumec) into the main channel. During this flood event, Champadanga had experienced a total 129 h of the flood while at Harinkhola the duration of the flood was 73 h when the gauge height remained higher than the Danger level (DL). At Champadanga and Harinkhola, the water level fell below the Primary Danger Level (PDL) on 04th August and 30th July respectively (Fig. 15a, b). Many villages of Jamalpur and Raina-II C.D. blocks of Purba Barddhaman district, Pursurah, Jangipara and Tarkeshwar C.D. blocks of Hooghly district, and Amta-I, Amta-II and Udaynarayanpur C.D. blocks of Howrah district located within the close proximity to the lower reach of the river were severely affected owing to inundation by floodwater and embankment breaching (Fig. 16). Quite a lot of roads, houses along with other anthropogenic structures have collapsed, several hectares of agricultural land with and without crops were inundated, and the smooth operation of the public lifestyle was totally disrupted (Fig. 17).

Therefore, all these combinedly made the life of riparian people miserable. There are more than 330,000 people residing in the villages located very close to the lower reach of the river (Census of India 2011), and severely affected by every flood event. Besides the riparian people, several socio-economic and socio-cultural structures like more than 20 educational institutes, 8 hospitals, 11 railway stations, 6 temples, 6 masjids, and several km of roads situated in the floodplains that can severely be affected due to the floodwater inundation. Thus, the future disastrous flood may increase human death, injuries, mental trauma and hamper human mobility, disrupt transport and communication system, health facilities, cultural practices, etc.

Conclusion

The famous nomenclature of the Damodar river as ‘Sorrow of Bengal’ has been modified after the implementation of DVC, and the present study discovers the changing nature of flood in the lower reach of the basin. After analysing three models, it can be said that the recurrence interval of flood expanded from 2 to 10 years or more during post dam period with a low magnitude of the flood having high-frequency probability. The most alarming forecast is that the lower basin again is going to experience megaflood event in and around 2030 with a magnitude of > 10,000 cumec of discharge. This would affect the region badly as it is a high populous region with huge socio-economic infrastructures within ten years from now. Therefore, immediate attention is needed from the administration and proper flood mitigation and preparedness plan should be formulated without any delay.

The rapid growth of the human population, settlements, socio-economic structures and anthropogenic activities increases human exposer and vulnerability to flood. The

Fig. 17 **a** Flood inundation of road and agricultural land at HetamChak village of Pursurah C.D. block, **b** house collapsed by flood water flow at Ghola village of Udaynarayanpur C.D. block, **c** part of Pursurah-Udaynarayanpur road broken by flood water flow near KurchiBinodbati village of Udaynarayanpur C.D. block, **d** flood inundated temple at Srirampur village of Pursurah C.D. block in 2017

indiscriminate anthropogenic interventions into the river system in terms of unscientific river bed mining leads to several chain reactions into the fluvial regime, such as lowering of bed, bar skimming, bank failure, embankment breaching, and lowering of ground water recharge to the aquifer, and ultimately hamper the total fluvial system of the lower reach. Thus, the existing flood situation along with its different attributes are aggravated by these anthropogenic interventions provide a great agony to the riverine people of its lower reach. This study unveils the need to upgrade the existing flood management systems along with control on indiscriminate anthropogenic interventions into the river system and a proper flood forecasting system could help the riverine people to save their life and property along with the natural system. These scientific steps basically help us in preparing the proper guideline of the sustainable development plan.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Agarwal A, Narain S (1996) Floods, floodplains and environmental myths. Centre for Science and Environment, New Delhi
Andrews J (1993) Flooding, Canada water book. Ecosystems Sciences and Evaluation Branch, Environment Canada, Ottawa
Bábek O, Faměra M, Hilscherová K et al (2011) Geochemical traces of flood layers in the fluvial sedimentary archive; implications for contamination history analyses. CATENA 87:281–290. https://doi.org/10.1016/j.catena.2011.06.014

Bhattacharyya K (1999) Floods, flood hazards and hazard reduction measures: a model-the case in the lower Damodar river. Indian J Landsc Syst Ecol Stud 22(1):57–68

Bhattacharyya K (2011) The lower Damodar river, India: understanding the human role in changing fluvial environment. Springer, Dordrecht

Blöschl G, Gaál L, Hall J et al (2015) Increasing river floods: fiction or reality? Increasing river floods. Wires Water 2:329–344. https://doi.org/10.1002/wat2.1079

Bubeck P, Otto A, Weichselgartner J (2017) Societal impacts of flood hazards. In: Campanella R (ed) Oxford research encyclopedia of natural hazard science. Oxford University Press

Castellarin A, Di Baldassarre G, Brath A (2011) Floodplain management strategies for flood attenuation in the river Po. River Res Applic 27:1037–1047. https://doi.org/10.1002/rra.1405

Census of India (2011) District census handbook—Barddhaman, Hugli and Howrah, 2011. Directorate of Census Operations, West Bengal, India

Chandra S (2003) India: flood management—Damodar river basin. http://www.apfm.info/pdf/case_studies/india.pdf. Accessed 25 Mar 2020

Chettri R, Bowonder B (1983) Siltation in Nizamsagar reservoir: environmental management issues. Appl Geogr 3:193–204. https://doi.org/10.1016/0143-6228(83)90026-7

Chiverrell RC, Sear DA, Warburton J et al (2019) Using lake sediment archives to improve understanding of flood magnitude and frequency: recent extreme flooding in northwest UK. Earth Surf Process Landf 44:2366–2376. https://doi.org/10.1002/esp.4650

Ciullo A, Viglione A, Castellarin A et al (2017) Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. Hydrol Sci J 62:880–891. https://doi.org/10.1080/02626667.2016.1273527

CRED-Centre for Research on the Epidemiology of Disasters (2015) The human cost of natural disasters 2015: a global perspective. http://cred.be/sites/default/files/The_Human_Cost_of_Natural_Disasters_CRED.pdf. Accessed 4 Apr 2020

Daesslé LW, Lugo-Ibarra KC, Tobschall HJ et al (2009) Accumulation of As, Pb, and Cu associated with the recent sedimentary processes in the Colorado Delta, South of the United States-Mexico Boundary. Arch Environ Contam Toxicol 56:680–692. https://doi.org/10.1007/s00244-008-9218-2

Dano U, Balogun A-L, Matori A-N et al (2019) Flood susceptibility mapping using GIS-based analytic network process: a case study of Perlis, Malaysia. Water 11:615. https://doi.org/10.3390/w11030615

Das SC, Sahu AS (2017) Flood zonation mapping through RS and GIS techniques: a case study in Panskura of Purba Medinipur district, West Bengal. Indian J Landsc Syst Ecol Stud 40(2):124–135

Dewan TH (2015) Societal impacts and vulnerability to floods in Bangladesh and Nepal. Weather Clim Extremes 7:36–42. https://doi.org/10.1016/j.wace.2014.11.001

Di Baldassarre G, Castellarin A, Brath A (2009) Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. Hydrol Sci J 54:1007–1017. https://doi.org/10.1623/hysj.54.6.1007

Di Baldassarre G, Kooy M, Kemerink JS, Brandimarte L (2013) Towards understanding the dynamic behaviour of floodplains as human-water systems. Hydrol Earth Syst Sci 17:3235–3244. https://doi.org/10.5194/hess-17-3235-2013

Dilley M, Chen RS, Deichmann U et al (2005) Natural disaster hotspots: a global risk analysis. World Bank Publications, Washington, D.C.

Doocy S, Daniels A, Murray S, Kirsch TD (2013) The human impact of floods: a historical review of events 1980–2009 and systematic literature review. PLoS Curr. https://doi.org/10.1371/currents.dis.f4deb457904936b07c09daa98ee8171a

DVC-Damodar Valley Corporation (1959) Report of the Committee for the Augmentation of Water Resources of DVC. Volume I, Calcutta

Ferrand E, Eyrolle F, Radakovitch O et al (2012) Historical levels of heavy metals and artificial radionuclides reconstructed from overbank sediment records in lower Rhône River (South-East France). Geochim Cosmochim Acta 82:163–182. https://doi.org/10.1016/j.gca.2011.11.023

Ferreira S (2011) Nature, socio-economics and flood-mortality. In: Proceedings of the 2011 Georgia water resources conference. University of Georgia, Athens, Georgia

Folk RL, Ward WC (1957) Brazos river bar: A study in the significance of grain size parameters. J Sediment Petrol 27(1):3–26

Ghosh S, Guchhait SK (2016) Dam-induced changes in flood hydrology and flood frequency of tropical river: a study in Damodar River of West Bengal, India. Arab J Geosci 9:90. https://doi.org/10.1007/s12517-015-2046-6

Gumbel EJ (1941) The return period of flood flows. Ann Math Stat 12:163–190. https://doi.org/10.1214/aoms/1177731747

Ho LTK, Umitsu M (2011) Micro-landform classification and flood hazard assessment of the Thu Bon alluvial plain, central Vietnam via an integrated method utilizing remotely sensed data. Appl Geogr 31:1082–1093. https://doi.org/10.1016/j.apgeog.2011.01.005

India Meteorological Department (2018) District wise rainfall-last 5 years. http://hydro.imd.gov.in/hydrometweb/(S(xxp0uuvbiamliw55gw5kya55))/DistrictRaifall.aspx. Accessed 20 Jan 2020

IPCC-Intergovernmental Panel on Climate Change (2007) In: Core Writing Team, Pachauri RK, Reisinger A (eds) Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland

IPCC-Intergovernmental Panel on Climate Change (2013) In: Stocker TF, Qin D, Plattner GK et al (eds) Climate change 2013: the physical science basis. contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jain V, Sinha R (2003) Geomorphological manifestations of the flood hazard: a remote sensing based approach. Geocarto Int 18:51–60. https://doi.org/10.1080/10106040308542289

Jones AF, Lewin J, Macklin MG (2010) Flood series data for the later Holocene: available approaches, potential and limitations from UK alluvial sediments. Holocene 20:1123–1135. https://doi.org/10.1177/0959683610369501

Kale VS (2005) Fluvial hydrology and geomorphology of monsoon-dominated Indian rivers. Rev Bras Geomorfol 6:63–73. https://doi.org/10.20502/rbg.v6i1.39

Karmokar S, De M (2020) Flash flood risk assessment for drainage basins in the Himalayan foreland of Jalpaiguri and Darjeeling Districts, West Bengal. Model Earth Syst Environ 6:2263–2289. https://doi.org/10.1007/s40808-020-00807-9

Khan B, Iqbal MJ, Yosufzai MAK (2011) Flood risk assessment of River Indus of Pakistan. Arab J Geosci 4:115–122. https://doi.org/10.1007/s12517-009-0110-9

Kontgis C, Schneider A, Ozdogan M et al (2019) Climate change impacts on rice productivity in the Mekong River Delta. Appl Geogr 102:71–83. https://doi.org/10.1016/j.apgeog.2018.12.004

Kundzewicz ZW, Kanae S, Seneviratne SI et al (2014) Flood risk and climate change: global and regional perspectives. Hydrol Sci J 59:1–28. https://doi.org/10.1080/02626667.2013.857411

Lewin J, Ashworth PJ, Strick RJP (2017) Spillage sedimentation on large river floodplains: spillage sedimentation on large river floodplains. Earth Surf Process Landf 42:290–305. https://doi.org/10.1002/esp.3996

Lintern A, Leahy PJ, Zawadzki A et al (2016) Sediment cores as archives of historical changes in floodplain lake hydrology. Sci

Total Environ 544:1008–1019. https://doi.org/10.1016/j.scitotenv.2015.11.153

Mondal GC, Singh AK, Singh TB (2018) Damodar river basin: storehouse of Indian coal. In: Singh DS (ed) The Indian rivers: scientific and socio-economic aspects. Springer Nature, Singapore, pp 259–272

Mosquera-Machado S, Ahmad S (2007) Flood hazard assessment of Atrato River in Colombia. Water Resour Manag 21:591–609. https://doi.org/10.1007/s11269-006-9032-4

Nikolova M, Nikolov V (2011) Assessment of the impact of geomorphologic and hydroclimatic factors on the flood hazard in river basins. Studia Geomorphologica Carpatho-Balcanica, vol XLV, pp 7–19

Pal SK (1998) Statistics for geoscientists: techniques and application. Concept Publishing Co., New Delhi

Peduzzi P (2006) The Disaster Risk Index: overview of a quantitative approach. In: Brikmann J (ed) Measuring vulnerability to natural hazards: towards disaster resilient societies. United Nations University Press, Tokyo, pp 176–186

Pradhan B (2010) Flood susceptible mapping and risk area delineation using logistic regression, GIS and remote sensing. J Spat Hydrol 9(2):1–18

Roy BC, Banerjee K (1990) Quaternary geological and geomorphological mapping in parts of Bardhaman and Bankura districts and preliminary assessment of sand deposits suitable for construction and other allied purposes. Progress report for the field season 1988–89. Regional Geology Division-I, Eastern region, Geological Survey of India, Calcutta

Sen PK (1985) The genesis of floods in the lower Damodar catchment. In: Sen PK (ed) The concepts and methods in geography. The University of Burdwan, Burdwan, pp 71–85

Sen PK (1991) Flood hazards and river bank erosion in the lower Damodar basin. In: Sharma HS (ed) Indian geomorphology. Concept Publishing Company, New Delhi, pp 95–108

Singh RK, Kumar Villuri VG, Pasupuleti S, Nune R (2020a) Hydrodynamic modeling for identifying flood vulnerability zones in lower Damodar river of eastern India. Ain Shams Eng J 11(4):1035–1046. https://doi.org/10.1016/j.asej.2020.01.011

Singh RK, Kumar Villuri VG, Pasupuleti S, Nune R (2020b) Hydrodynamic modeling for identifying flood vulnerability zones in lower Damodar river of eastern India. Ain Shams Eng J 11:1035–1046. https://doi.org/10.1016/j.asej.2020.01.011

Singh RK, Soni A, Kumar S, Pasupuleti S, Govind V (2021a) Zonation of flood prone areas by an integrated framework of a hydrodynamic model and ANN. Water Supply 21(1):80–97. https://doi.org/10.2166/ws.2020.252

Singh RK, Soni A, Kumar S et al (2021b) Zonation of flood prone areas by an integrated framework of a hydrodynamic model and ANN. Water Supply 21:80–97. https://doi.org/10.2166/ws.2020.252

Subramanya K (2008) Engineering hydrology, 3rd edn. Tata McGraw-Hill Publishing Company Limited, New Delhi

Tola SY, Shetty A (2022) Flood susceptibility modeling based on morphometric parameters in Upper Awash River basin, Ethiopia using geospatial techniques. Sustain Water Resour Manag 8:49. https://doi.org/10.1007/s40899-022-00642-z

Toonen WHJ, Foulds SA, Macklin MG, Lewin J (2017) Events, episodes, and phases: signal from noise in flood-sediment archives. Geology 45:331–334. https://doi.org/10.1130/G38540.1

Tripathi R, Sengupta SK, Patra A et al (2014) Climate change, urban development, and community perception of an extreme flood: a case study of Vernonia, Oregon, USA. Appl Geogr 46:137–146. https://doi.org/10.1016/j.apgeog.2013.11.007

UNDP-United Nation Development Programme (2004) Reducing disaster risk: a challenge for development. United Nations Development Programme, Bureau for Crisis Prevention and Recovery, New York

Vörösmarty CJ, McIntyre PB, Gessner MO et al (2010) Global threats to human water security and river biodiversity. Nature 467:555–561. https://doi.org/10.1038/nature09440

Watt WE (ed) (1989) Hydrology of floods in Canada: a guide to planning and design. National Research Council of Canada, Ottawa

Whitfield PH (2012) Floods in future climates: a review: changing floods in future climates. J Flood Risk Manag 5:336–365. https://doi.org/10.1111/j.1753-318X.2012.01150.x

Wilhelm B, Ballesteros Cánovas JA, Macdonald N et al (2019) Interpreting historical, botanical, and geological evidence to aid preparations for future floods. Wires Water 6:e1318. https://doi.org/10.1002/wat2.1318

Wolfe BB, Hall RI, Last WM et al (2006) Reconstruction of multi-century flood histories from oxbow lake sediments, Peace-Athabasca Delta, Canada. Hydrol Process 20:4131–4153. https://doi.org/10.1002/hyp.6423

Woo M, Waylen PR (1986) Probability studies of floods. Appl Geogr 6:185–195. https://doi.org/10.1016/0143-6228(86)90001-9

Woube M (1999) Flooding andsustainable land–water management in the lower Baro-Akobo river basin, Ethiopia. Appl Geogr 19:235–251. https://doi.org/10.1016/S0143-6228(99)00004-1