Chapter 4
The Reservoired Lower Damodar River: A Hydro-Geomorphic Perspective

Abstract Rivers respond to anthropogenic activities through morphological and hydrological adjustments in the channel. This chapter addresses the hydromorphological consequences of the control structures on the Damodar River. Dams have altered the flow regime, channel characteristics and the sediment supply of the river. Under natural flow conditions, on an average, 12 days per year experienced a flow above 2,265.6 m^3/s. This has decreased to 4 days under artificial conditions. Monsoon streamflow has been reduced, but non-monsoon flow has increased albeit with a very high variability in the post-dam period. The R.I. of the bankfull stage, a flow of 7,080 m^3/s in the pre-dam period, increased from 2 to 14 years in the post-dam period. The magnitude of the design flood from Maithon and Panchet reservoirs has been reduced by about 56%. During the non-monsoon period canal discharge in most cases exceeds the river discharge. The low volume of water released downstream during dry months virtually transforms this section into a sandy waste whereas the high discharge released during monsoon months converts the section to a vigorous flowing channel. Although some sediment is trapped in the reservoirs, a million tons of sediment nevertheless pours into the river from the uncontrolled stretch. Capacity of the river to transport this sediment has been reduced due to the reduction of flood peaks. A chain of sandbars has emerged within the riverbed below the control structures. The channel deposits in the study area support agriculture and most of the channel bars have been settled and are now used as a resource base, mostly by Bangladeshi refugees.

Keywords Anthropogenic · Dams · Flow-regime · Hydromorphological · Monsoon streamflow · Refugees · Reservoirs · Sandbars · Sediment

4.1 Damodar: A "Reservoir Channel"

Any river unaffected by human controls attains a state of equilibrium due to the complex interplay of many interdependent variables such as discharge, sediment, and channel characteristics. A natural river system is an open system in dynamic equilibrium in which dependent variables such as river channel slope, gradient, and

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planform get adjusted to the inputs of water discharge and sediment load. If changes occur in any of these inputs, the system responds immediately by adjusting its morphology. River control measures disturb this state of equilibrium (Bhattacharyya 1998). In the Damodar River, human modifications of the natural system have altered the flow regime, flood behavior, and the sediment supply of the river. Fluvial systems have been affected by the construction of control structures such as barrages and dams. In this study, historic streamflow, rainfall and sediment data have been collected and analyzed in order to document these changes.

Dams, barrages, and weirs normally belong to the category of transverse control structures with which the present study is concerned. Regulators, sluices, and canals are also included in this category since discharge and sedimentation below these points are also related to these control structures. Typically, the impacts of transverse control structures cannot be isolated from those due to lateral control structures. Some of the noticeable changes, however, were recorded only after dam closure. Therefore, it may be safely assumed that these changes followed the construction of the major control structures. In the following paragraphs, the impacts of transverse control structures, focusing primarily on dams are examined.

The impacts of dams on the flow regime, sediment and channel characteristics of the Damodar River during the period between 1933 and 2007 are assessed. Further topics of discussion will include changes in suspended sediment concentration, silting of reservoirs, changes in bed slope, change in the sinuosity index of the Lower Damodar thalweg, change in channel characteristics, the stabilization of bars after dam closure, and shifting bank lines and bank erosion. Finally, the present condition of the Jamalpur regulator, the Jujuti sluice, the Eden canal and the Ulughata sluice will be reviewed.

For a comparative analysis of the changes in the river regime of the Lower Damodar River, data from 1933 to 2007 have been divided into two periods, the pre-dam period between 1933 and 1956, and the post-dam period between 1959 and 2007.

4.2 Impacts of Dams: Changing Flow Regime

One of the important variables in a fluvial system is river discharge (Schumm 1977). Both base flow and the episodic flows are most important in maintaining a fluvial landscape. The base flow, average flow and peak flow in the pre-dam and post-dam periods are analyzed here based on hydrological observation (Appendix B) to assess the effects of the major control structures on the lower Damodar River.

4.2.1 Daily, Monthly Mean, and Annual Flow Characteristics

In the 10-year record (1940–1949) of the Damodar streamflow at Rhondia, about 62.6% of the days experienced a flow of less than 2,83.2 m^3/s (10,000 cusec) and 3.4% experienced a flow above 2,265.6 m^3/s (80,000 cusec). During the post-dam period (1993–2007) (Table 4.1), about 71.92% of the days experienced a flow less

Table 4.1 Frequency of daily streamflow of the lower Damodar at Rhondia in pre-dam (1940–1949) and post-dam (1993–2007) periods

	Percentage of total number of days		
Class unit in m^3/s	Pre-dam	Post-dam	Percentage change
Below 283.2	62.60	71.92	+14.89
283.2–566.4	7.00	9.00	+28.57
566.4–849.6	5.30	4.90	–7.55
849.6–1132.8	3.70	2.50	–32.43
1,132.8–1,416	2.80	1.60	–42.86
1,416–1,699.2	2.20	1.23	–44.09
1,699.2–1,982.4	1.50	0.75	–50
1,982.4–2,265.6	1.50	0.30	–80
Above 2,265.6	3.44	1.20	–65.12
Percentage of no flow days	9.96	6.5	–34.74
	100%	100%	

Total number of days in pre-dam period = 3,653. Total number of no flow days = 364. Total number of days in post-dam period = 5,425. Total number of no flow days = 367. Data not available = 53 days.
Data Source: Appendix B

than 2,83.2 m^3/s, a percentage increase of about +14.89, whereas only 1% of the days experienced a flow above 2,265.6 m^3/s, a percentage change of about –65.12. Under natural conditions mean daily flow fell below 2,83.2 m^3/s 229 days per year increasing slightly to 261 days between 1993 and 2007 whereas, under natural conditions, 12 days on average in a year experienced a flow above 2,265.6 m^3/s which has decreased to 5 days under controlled conditions. The total number of no-flow days was 364 i.e. 9.96% in the pre-dam period, whereas no-flow days in the post-dam period are 367 which is 6.76%. In the post-dam period daily streamflow of 566.4–849.6 m^3/s (20,000–30,000 cusec) to above 2,265.6 m^3/s shows a negative trend (Table 4.1). The representative daily average streamflow for the Damodar at Rhondia is 381 m^3/s in the pre-dam and 245 m^3/s in the post-dam period (Fig. 4.1).

During the pre-dam period (1953–1955), about 78.21% of days experienced a flow less than 566.4 m^3/s at the Damodar Bridge site but in the post-dam period (1983–1990) about 68.15% of the days experienced a similar flow (Table 4.2) indicating a relatively wetter condition in the post-dam period. A release from dams throughout the year provides a median of about 137.71 m^3/s with a mode of 103.91 m $^3/s$ for the year 1975. However, the median and modal values for 1955 were 91.96 and 75.50 m^3/s respectively (Sen 1978).

The average daily streamflow for a given year is computed by taking the average streamflow data during each day calculated from hourly streamflow, adding these for 365 consecutive days, and dividing the total by 365 or by the total number of days of data availability. To get a representative daily streamflow, these annual figures for a number of years have been averaged. Similarly, monthly and annual total streamflow

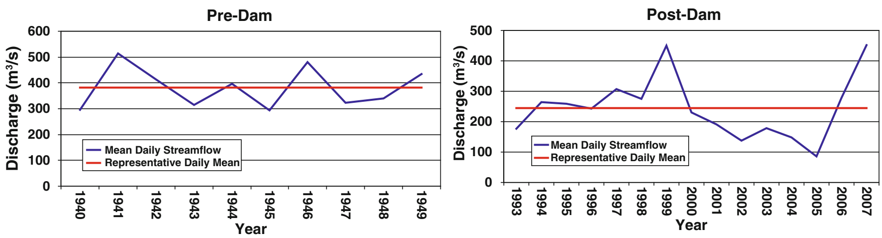

Fig. 4.1 Characteristics of daily discharge and representative daily average discharge of the lower Damodar River at Rhondia in pre-dam (1940–1949) and post-dam (1993–2007) periods
The average daily discharge for a given year is computed by taking the average discharge during each day calculated from hourly discharge and adding these for 365 consecutive days and dividing the total by 365 or by total number of days of data availability. To get a representative daily discharge these annual figures for a number of years have been averaged. Similarly monthly and annual peak discharges were averaged. Frequency of daily discharge and the percentage change has been computed.

Table 4.2 Frequency of monsoon streamflow of the lower Damodar River at Damodar bridge site in pre-dam (1953–1955) and post-dam (1983–1990) periods

Pre dam	
Total number of days – 459	
Class unit (m^3/s)	Percentage to total number of days
Below 566.4	78.20
566.4–1,132.8	15.60
1,132.8–1,699.2	3.70
1,699.2–2,265.6	1.18
Above 2,265.6	1.31
Post dam	
Total number of days – 1,193	
Class unit (m^3/s)	Percentage to total number of days
Below 566.4	68.15
566.4–1,132.8	16.26
1,132.8–1,699.2	7.96
1,699.2–2,265.6	3.70
Above 2,265.6	3.93

Data Source: Hydraulic Data Division, DVC, Maithon.

were averaged. Frequency of daily streamflow, as well as the percentage change, has also been computed.

Time series analysis, showing the variation of streamflow of the Damodar at Rhondia in the pre and post-dam periods, is shown in Fig. 4.2.

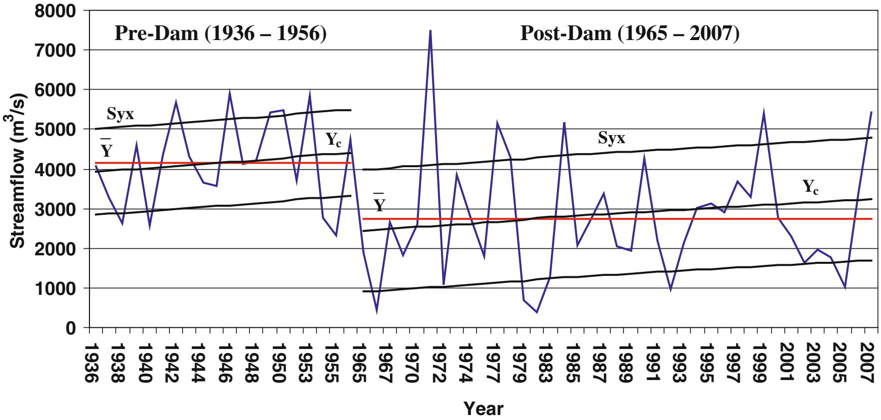

Fig. 4.2 Trend of mean annual discharge of the lower Damodar River at Rhondia in pre-dam (1936–1956) and post-dam (1965–2007) periods
Yc = 4161.5 + {(−24.26)x}, Syx = 1, 084 m3/s, Average Streamflow (Y) = 4, 162 m3/s (pre-dam)
Yc = 273.97 + {(−66.73)x}, Syx = 1, 533 m3/s, Average Streamflow (Y) = 2, 737 m3/s (post-dam)
Data Source: Refer to Appendix B

There,

$$Yc = a + bx$$

where

Yc = estimated streamflow
a = value of y where x = 0
b = rate of change of y per unit of x,
x = deviation of the actual streamflow from the mean streamflow

The trend lines are Yc = 4161.5 + {(−24.26) x} for the pre-dam period and Yc = 2736.97 + {(−66.73) x}, for the post-dam period. It is expected that the discharge will vary on either side of the trend line. In both cases the trend lines show a decrease. From Fig. 4.2 it is clear that discharge was increased after 1935 due to the depression after the First World War when work in most of the industries had stopped reducing the demand for water in the industrial sector and resulting in an enhanced average streamflow. The decreasing trend in the pre-dam period was due to extraction of water by industries in the Damodar valley. The range of fluctuation has increased during the post-dam period, as shown by the standard error of estimate or Syx which is 1,084 m^3/s for the pre-dam period increasing to 1,544 m ^{3}/s for the post-dam period. An increase in the range of fluctuation in that period indicates that the release below the Durgapur barrage corresponds to the demand of water for canal consumption and uncertainty in the amount of rainfall. It is also true that

Table 4.3 Streamflow characteristics of Damodar River at Rhondia in pre-dam (1934–1956) and post-dam (1959–2007) periods (% of streamflow with respect to mean annual streamflow total)

Period	Parameter	Summer	Monsoon	Autumn	Winter	Mean annual total (m^3/s)
Pre-dam	N	21	21	21	21	21
	X	1.40	83.70	12.23	2.60	4,061.05
	s.d	1.32	7.04	6.49	2.27	1,186.90
	c.v	94.29	8.41	53.07	87.31	29.23
Post-dam	N	48	48	48	48	48
	X	5.07	75.58	14.60	5.22	2,836.02
	s.d	6.67	13.81	12.11	4.58	1,587.34
	c.v	131.56	18.27	82.95	87.74	55.97

N = No of years, X = Average % of flow, s.d = standard deviation, c.v. = coefficient of variation. Summer – March to May, Monsoon – June to September, Autumn – October – November, Winter – December to February.
Data Source: Computed by the author based on processed data in Appendix C.

water is released downstream, not according to natural cycles, but as dictated by the region's hour-by-hour needs for irrigation and other purposes.

The discharge of the Damodar at Rhondia and at the Damodar bridge site for four climatologic seasons with respect to the total annual flow from 1934 to 2007 for Rhondia and 1953–2007 for the Damodar Bridge site is given in Tables 4.3 and 4.4. Flow at Rhondia shows a sharp contrast between the pre-dam and post-dam periods. During the summer season (March–May) the mean percentage of flow shows a significant increase from 1.40 to 5.07%, but with a large standard deviation (6.67) and very high variability (131.56) during the post-dam period. The mean autumn (October–November) discharge shows a marginal increase but with large standard deviation and variability. The same is true for the winter (December–February)

Table 4.4 Streamflow characteristics of Damodar River at Damodar bridge site in pre-dam (1953–1955) and post-dam (1969–2007) periods (% of flow with respect to mean annual streamflow total)

Period	Parameter	Summer	Monsoon	Autumn	Winter	Mean annual total (m^3/s)
Pre-dam	N	3	3	3	3	3
	X	2.81	84.25	8.68	4.26	63,193.99
	s.d	1.91	7.14	3.91	1.34	23,811.31
	c.v	67.97	8.47	45.05	31.46	37.68
Post-dam	N	27	27	27	27	27
	X	4.89	76.38	15.25	3.48	68,457.87
	s.d	3.96	13.11	10.43	2.89	37,294.81
	c.v	80.98	17.16	68.39	83.05	54.48

N = No of years, X = Average % of flow, s.d = standard deviation, c.v. = coefficient of variation. Summer – March to May, Monsoon – June to September, Autumn – October – November, Winter – December to February.
Data Source: Computed by the author based on processed data in Appendix D.

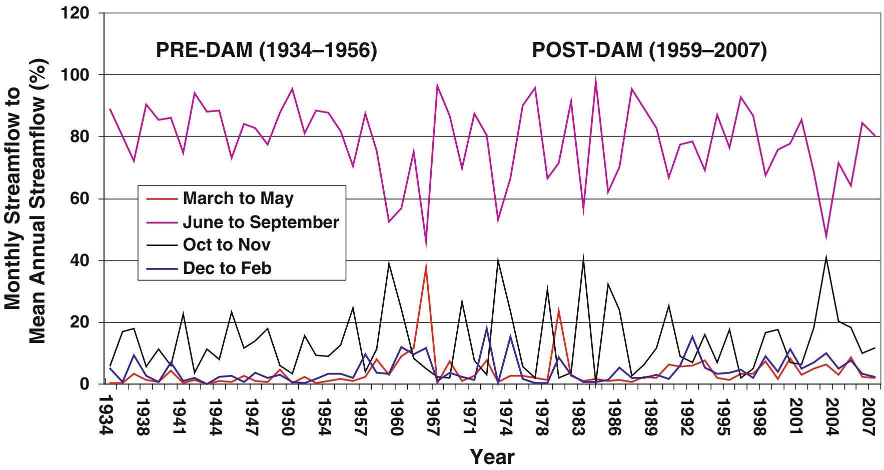

Fig. 4.3 Discharge characteristics of the lower Damodar River at Rhondia in pre-dam (1934–1956) and post-dam (1959–2007) periods (percentage of streamflow with respect to mean annual total streamflow). Data source: Appendix C

discharge. The mean monsoon discharge (June–September) shows a decrease in the post-dam period but with large standard deviation and variability as well. The total annual discharge during the pre-dam period was much higher than that in the post-dam period; deviation and variability have both increased during the post-dam period. The most important characteristic is that there has been at least a 30% decrease in average annual discharge from the pre-dam to the post-dam period and nearly a 48% increase in variability (Fig. 4.3; Appendix C).

Flow at the Damodar Bridge site shows that summer and autumn discharge has increased significantly from the pre-dam to the post-dam period while monsoon flow has decreased significantly from 84 to 76% in the post-dam period. There has been at least an 8% increase in mean annual discharge from the pre-dam to the post-dam period and nearly 31% increase in variability (Table 4.4; Appendix D). Regarding total annual streamflow, the significant increase is interestingly associated with low variability. After dam closure monsoon flow has been reduced due to control by dams. The water is released during the non-monsoon period (i.e. in summer, autumn and winter) to the Durgapur barrage from which water is diverted to canals for irrigation. Increasing demand for irrigation water has enhanced the non-monsoon flow to some extent. Thus, there is considerable augmentation of flow in the lean season mitigating the non-monsoon demand for irrigation. An irrigation system dependent on rainfall and river discharge has been replaced by fully assured irrigation through regulated release from reservoirs. Much of the surplus water that used to flow down the river is now stored in the reservoirs. The reservoir releases correspond to the actual requirements of crops and hydropower generation.

The purpose of reservoirs is to store a significant amount of surplus rainfall draining into the parent channel. The stored water is then distributed through canals

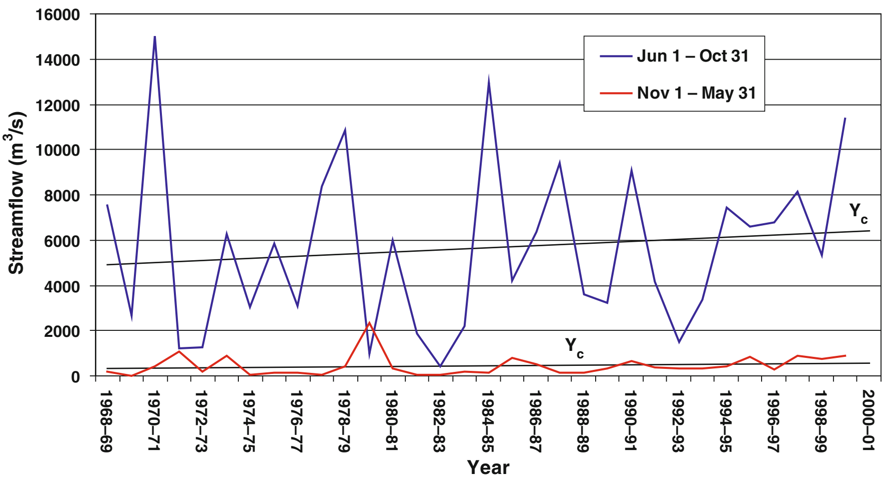

Fig. 4.4 Trend of monsoon and non-monsoon discharge of the lower Damodar River below the Durgapur Barrage (Data source: Appendix B)

whenever necessary. The magnitude of canal flow (Y) from the Durgapur barrage depends on total inflow (x) into the barrage from the Maithon and Panchet combined outflow. A linear regression model of the form $Y = a + bx$ has been worked out for different years for data extending over 12 months (Appendix E). The variables show a conformal positive relation $r = 0.81$.

A time series analysis showing variations in discharge released down the Durgapur barrage for the period extending from June to October and again from November to May has been performed. The trend lines in both periods move in a positive direction. Hence, both the monsoon and non-monsoon flows from the Durgapur barrage show an increase in discharge (Fig. 4.4). Volume of water released to flow down the Durgapur barrage and canals (left bank and right bank) are also shown diagrammatically (Fig. 4.5). During the non-monsoon period (November–May), canal discharge in most cases exceeds river discharge. Low volumes of water released into the river below the barrage during dry months virtually transform this section into a sandy waste whereas high discharge during the monsoon season converts this section to a vigorous flowing channel.

4.2.2 *Changes in Peak Flow Characteristics*

The presence of storage reservoirs and the barrage on the Damodar disrupts its equilibrium leading to a series of changes in the fluvial system. In such a channel water stored behind a dam and gradually released results in marked reduction in the magnitude and frequency of peak streamflow disturbing the stable channel equilibrium as well as the flow regime (Williams and Wolman 1984; Kondolf 1997; Chin et al. 2002; Magilliigan and Nislow 2001, 2005; Graf 2006; Bhattacharyya

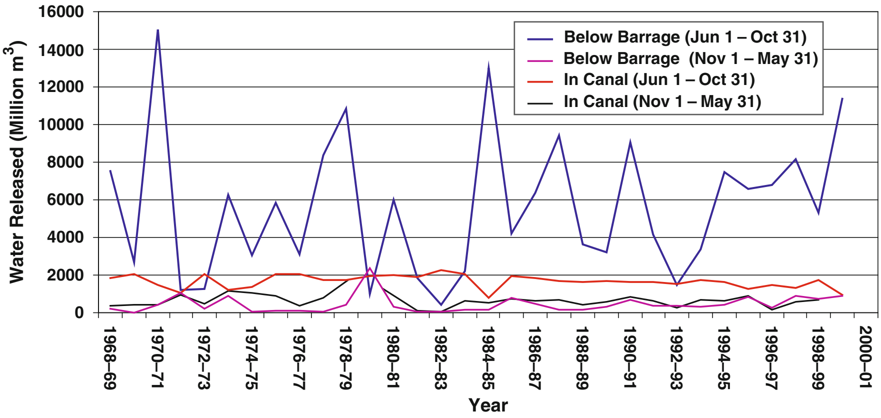

Fig. 4.5 Volume of water supplied down the Durgapur Barrage and left and right bank main canal
Irrigation potential has been drastically increased below barrage. Kharif crops are sown after the first shower of monsoon, and are harvested after the last spell of monsoon. Rabi crops are winter crops, sown in autumn and harvested in spring. Kharif irrigation was extended to 82,600 acres (3,34,274 ha) by the end of the 1999 Kharif season, against the target of 9,73,000 acres (3,93,763 ha). Rabi (winter crops harvested in spring) irrigation has been extended to 52,000 acres (21,044 ha) against the target of 55,000 acres (22,258 ha). With the popularity of Boro (paddy) cultivation due to its high yielding variety, farmers are trying to bring more and more area under Boro irrigation. As it is a summer (February to May) crop, water requirement for Boro irrigation is quite high and is dependent mainly on surface water released from the reservoirs and ground water
Data Source: Refer to Appendix E

1998, 1999–2000b, 2008; Richter et al. 2010). Similar results have been observed in numerous large watersheds around the world. For example, Dolan et al. (1974) have recorded a 60% reduction in the magnitude of the mean annual flood on the Colorado River below the Hoover Dam. William and Wolman (1984) have noted that average annual peak discharges from 21 sites from the US Geological Survey were decreased from 3 to 91% of their pre-dam values averaging about 39%. For the Damodar river, the average annual peak streamflow recorded at the Rhondia gauging site has been decreased to 57% of its pre-dam (1933–1956) value (Figs. 4.6 and 4.7). The average peak streamflow at Rhondia decreased to 3,607 m^3/s in the post-dam period (1959–2007) from the pre-dam (1933–1956) flow of 8,413 m^3/s and the Pre-Rhondia (1823–1917) flow of 11,651 m^3/s.

A time series analysis has been done on the basis of the data given in Appendix F to show the peak streamflow characteristics of the Damodar in the pre-dam and post-dam period, and is shown in Fig. 4.6. The equation for the trend line is $Y_C = a + bx$ where

Y_c = estimated streamflow
a = value of y where x = 0
b = rate of change of y per unit of x,
x = deviation of the actual streamflow from the mean streamflow

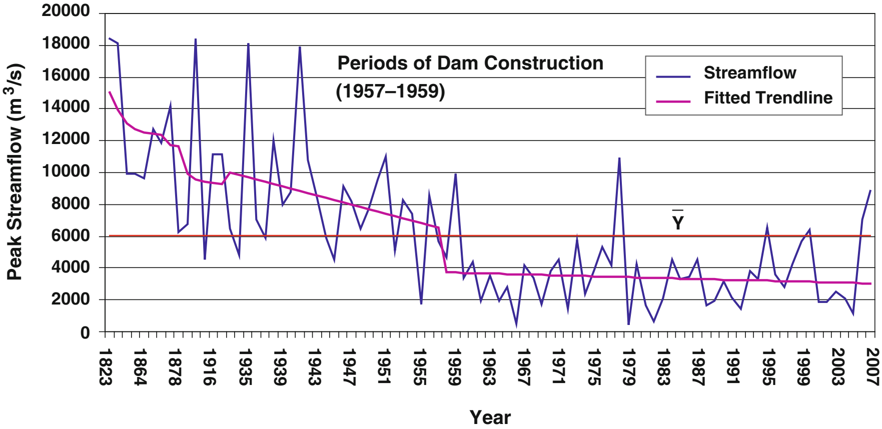

Fig. 4.6 Peak streamflow characteristics of the lower Damodar River at Raniganj (data shown before 1933) and at Rhondia (data shown from 1933 to 2007). Data Source: Refer to Appendix F

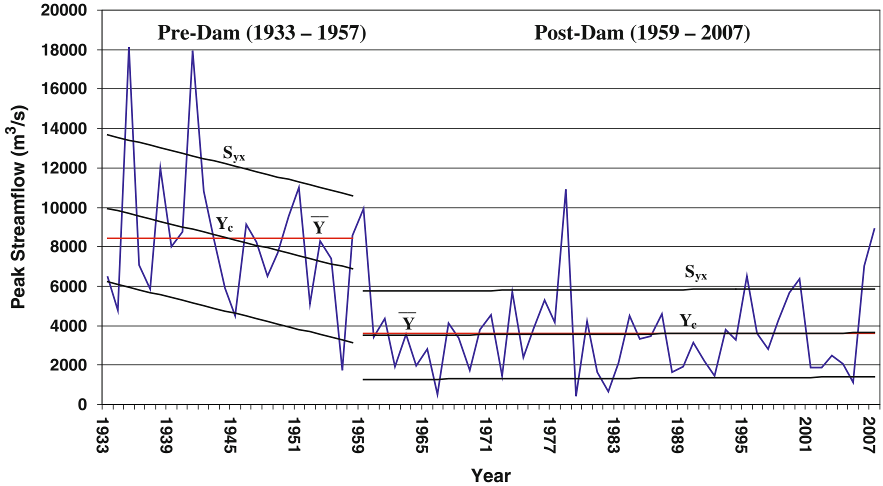

Fig. 4.7 Trend of peak flow of the lower Damodar River in pre-dam and post-dam periods
Yc = 8412.5+{(−133.87)} x, S*yx* = 3, 988 m3/s, Average peak discharge (Y) = 8, 413 m3/s (Pre-dam, 1933–1956)
Yc = 3564.95 + {(−2.69)} x, S*yx* = 2, 241 m3/s, Average peak discharge (Y) = 3, 607 m3/s (Post-dam, 1959–2007)
Data Source: Refer to Appendix F

Figure 4.6 shows a decrease of peak flood in both periods. In the pre-dam period, the peak flow decreases gradually due to extraction of water by industry with a trend line $Yc = 8,412.5 + \{(-133.87)\}x$. As expected, the peak discharge varies on either side of the trend line. In the pre-dam period the standard error of estimate is $\pm 3{,}988$ m ^{3}/s.

In the pre-dam period, in any year, the actual peak streamflow may be expected to lie within 3,988 m^3/s on either side of the computed peak discharge. The peak discharges of 18,112 m^3/s (1935) and 17,942 m^3/s (1941) are abnormally high, exceeding the expected range of discharge fluctuations as given by Syx±3,988 m^3/s. The actual departures in these 2 years were +8,427.74 and +9,060.96 m^3/s respectively. These two high peak floods are clearly outliers. Similarly, the peak discharges of 4,793 m^3/s (1934) and 1,714 m^3/s (1955) are abnormally low, exceeding the normal range of discharge fluctuations as given by Syx ± 3,988 m^3/s. The actual departures in these 2 years were –5,025.14 and –5,292.87 m^3/s respectively. In the post-dam period, the trend line follows the equation of $Yc = 3,607.42 + \{(-56.74)\}x$, and in that period the standard error of estimate (Syx) is ±2,241 m^3/s. The peak discharges of 8,792 m^3/s (1959), 10,919 m^3/s (1978) and 8,883 m^3/s (2007) are abnormally high and the discharges of 6,522 m^3/s (1995) and 6,387 m^3/s (2000) also exceed the expected range of discharge fluctuation of ±2,241 m^3/s. The peak discharge figures of 503 m^3/s (1966), 413 m^3/s (1979) and 666 m^3/s (1982) are abnormally low and are designated as drought years (Bhattacharyya 1998).

4.2.3 Modification of Hydrographs in the Post-dam Period

Due to regulation of the reservoirs, flood peaks were significantly reduced after dam construction. Under natural conditions, i.e. in the pre-dam period, floods occurred mostly in July or August. In the post-dam period, however, the August floods are kept in check by filling the DVC dams full to the brim. In the hydrological cycle, water infiltrates the ground up to July–August whereas in September, the soil becomes completely saturated and water flows to the river. There is local belief that rainfall in the “Hathia” (the period between September 25th and October 10) is very crucial to the yield of rice. Hence, water is stored behind dams to be released to meet the probable shortage in September and October. If it happens to rain in September, however, water stored behind the dam has to be released in all its fury; the consequence is an inevitable flood (Bhattacharyya 1998). From the hydrographs of the Damodar at Rhondia in pre-dam and post-dam periods, it is found that peak streamflow has been shifted from August in pre-dam to September in the post-dam period (Fig. 4.8). It is worth noting here that the devastating floods of 1978 occurred in the month of September (Fig. 4.9).

4.2.4 Flood Hydrology

Floods are hydrological events, independently distributed in time and characterized by their magnitude and recurrence interval (Sharma 1976). The magnitude of an extreme event is inversely related to its frequency of occurrence i.e., very severe events occur less frequently than more moderate events. The annual maximum discharge is often used in developing a flood frequency distribution.

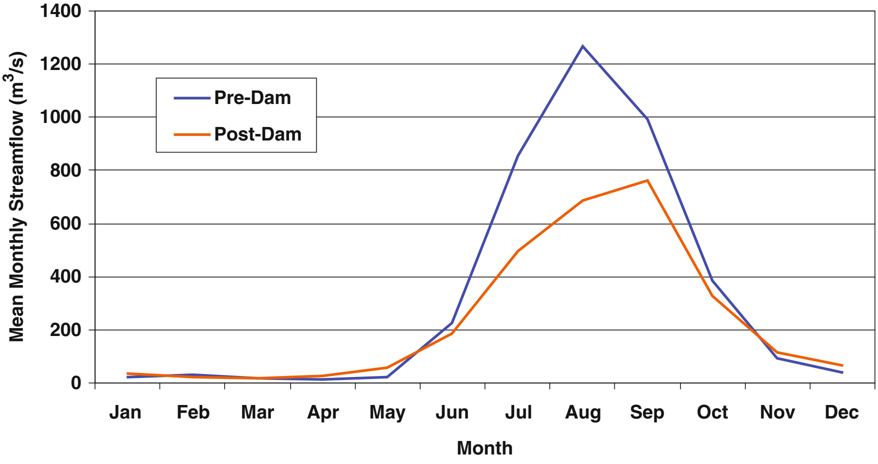

Fig. 4.8 Hydrographs of the lower Damodar River in pre-dam (1934–1956) and post-dam (1959–2007) periods
The representative average monthly streamflow for the pre-dam (1934–1956) and post-dam (1959–2007) is computed by taking the average streamflow during each month, adding these for the period 1934–1956 and 1959–2007, and dividing the total by number of months of data availability.
Data Source: Refer to processed data in Appendix C

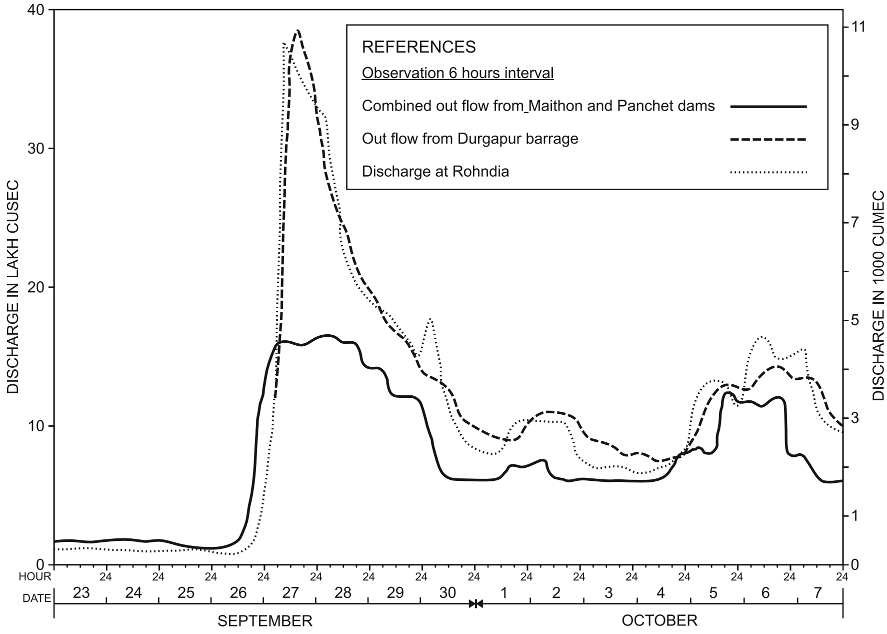

Fig. 4.9 Flood hydrographs of the lower Damodar River at different sites during Sept–Oct 1978 flood (Data source: PK Sen 1993)

There are several methods for flood frequency analysis. These methods consider either full or partial series. A series is constituted by the recorded events of peak flows over a given period of time. In the full series only the highest magnitude of flood during a given year and in the partial series flood occurrences more than once above the assumed magnitude is considered for analysis. The full series may be analyzed for flood frequency by several of the empirical, statistical or graphical methods (Chow et al. 1988; Sharma 1976). Hydrologic systems are sometimes affected by extreme events such as severe storms, floods etc. In this analysis the first asymptotic distribution of extreme values (Gumbel 1941) has been used in order to compute annual flood data.

Under the natural condition the mean annual flood (q2.33) and the most probable annual flood (q1.58) are of the order of 8,417 and 6,728 m^3/s respectively whereas 7,000 m^3/s has a recurrence interval of only 1.67 years. The bankfull stage of 7,080 m^3/s has a recurrence interval of 1.7 years. Thus the Damodar at the hydrometric station was subjected to frequent floods in and around Rhondia and in the entire trans-Damodar catchment i.e., below Paikpara. Discharges of 10,000 and 20,000 m^3/s have recurrence intervals of 3.60 and 96.41 years respectively (Bhattacharyya 1998, 2000b). In the post-dam period (1959–2007), the regulated flow due to dam closure does not actually conform to the theory of extreme values. For want of a proper statistical hypothesis to deal with the distribution of such hydrologic phenomena, the asymptotic theory, as has been applied to extreme yearly floods under natural conditions of the watershed, has been applied for the post-dam period (Sharma 1976).

Under the artificial conditions of the catchment, the mean annual flood and most probable annual flood are of the order of 3,630 and 2,604 m^3/s respectively, flows well below the bankfull stage at Rhondia. The return period for the bankfull stage of 7,080 m^3/s has been increased to 14 years. In probabilistic terms, a 14-year flood means a 1-in-14 chance of occurring in any given year. So it is evident from the above that the probability of occurrence of floods has been reduced during the post-dam period. The return period of floods of 10,000 m^3/s has been increased from 4-year, pre-dam, to 66-year, post-dam, and shows the definite flood moderation capability of the DVC dams (Tables 4.5, 4.6, 4.7).

According to available data (Appendix F), peak floods exceeding 10,000 m^3/s at Rhondia occurred five times before dam closure between 1933 and 1957. After dam closure, combined peak inflow of 10,000 m^3/s in the DVC dams (Maithon and Panchet) occurred fourteen times (Table 4.6; Appendix G; Fig. 4.10). During October 1959, peak inflow into the reservoirs of 17,641 m^3/s was moderated to 8,155 m^3/s. The outflow recorded at Durgapur barrage was 9,911 m^3/s due to the contribution from the intermediate catchment. "It has been recorded by the DVC that had there been no dams, a flood of 22,939 m^3/s would have been experienced below the Durgapur barrage which was much higher than the highest recorded flood of 18,406 m^3/s till that time" said DVC Engineer, Debashis Ghosh (personal communication March 14, 1997). Highest combined inflow at Maithon and Panchet has been recorded as 21,070 m^3/s on September 27, 1978. This was moderated to the combined outflow of 4,616 m^3/s (Tables 4.6, 4.7). It is evident from the Table 4.6

Table 4.5 Flood frequency analysis

Periods	$\overline{X}$ (m^3/s)	s.d	Recurrence interval In years for discharge (m^3/s) value of				$q^{1..58}$ (m^3/s)	$q^{2..33}$ (m^3/s)
			7,000	7,080	10,000	20,000		
Pre-dam (1934–(1956)	8,413	3,730	1.67	1.7	4	96	6,728	8,417
Post-dam (1959–(2007)	3,607	2,265	12.51	14	66	18,811	2,607	3,630

Most probable flood ($q = 1.58$ years, Peak discharge corresponding to a return period of 1.58 years
Mean annual flood (q =2.33 years, Peak discharge corresponding to a return period of 2.33 years).
Computed by the author based on data in Appendix F

Table 4.6 Performance of Damodar valley reservoirs (Maithon and Panchet) in combined flood moderation during major flood periods

Periods	Combined peak inflow 1,000 m^3/s	Moderated outflow 1,000 m^3/s	Flood moderation 1,000 m^3/s	Flood moderation achieved
Sept, 1958	15.7	5.0	10.7	68
Oct, 1959	17.6	8.2	9.5	53
Oct, 1960	9.9	2.6	7.2	73
Oct, 1961	14.6	4.6	10.1	68
Jul, 1963	12.8	3.4	9.4	73
Oct, 1963	13.2	2.6	10.6	80
Sep, 1971	12.0	5.1	6.9	58
Sep, 1973	16.7	5.0	11.7	70
Sep, 1978	21.9	4.6	17.3	79
Sep,1995	17.5	7.1	10.4	59
Sep, 1999	10.3	3.4	6.9	67
Sep, 2000	10.8	5.7	5.3	47
Sep, 2006	14.4	6.9	7.5	52
Sep, 2007	11.1	7.5	3.6	32

Examination of maximum inflow and maximum outflow data for the two lower dams at Maithon and Panchet show that flood moderation has been achieved during major flood years. Detailed examination of flow data, as available at Rhondia, revealed that maximum flow of 18,408 m^3/s had occurred twice in August 1913 and 1935 before the implementation of the DVC but data shows that major floods nearing or exceeding this maximum observed flood of 18,406 m^3/s occured during 1959, 1978 and 1995 and were successfully checked.
Data Source: DVC (1995), MRO office, DVC Maithon.

that flood moderation to the extent of 32–80% had been achieved in the high flood years. Detailed examination of flow data as available from 1958 to 2007 from the DVC record shows (Appendix G) that the magnitude of the design flood from the Panchet and Maithon has been reduced by an average of 56% due to flood management by DVC dams. Jain et al. (1973) reported that the magnitude of the design flood

Table 4.7 Performance of Damodar valley reservoirs (Maithon and Panchet) in 1978 flood (m^3/s)

	With 4 DVC dams		Without dams	
	3 Hourly peak inflow	3 Hourly peak outflow	3 Hourly peak inflow	3 Hourly peak outflow
At Maithon and Panchet	21,917	4, 615	26,958	26,958
At Durgapur	10,732	10, 732	33,414	33,414

Without dam intervention, the river would have generated a probable peak of 33,414 m^3/s at Durgapur barrage, thus exceeding the design flood of 28,320 m^3/s.
Computed by the author based on data availability shown in Appendix F

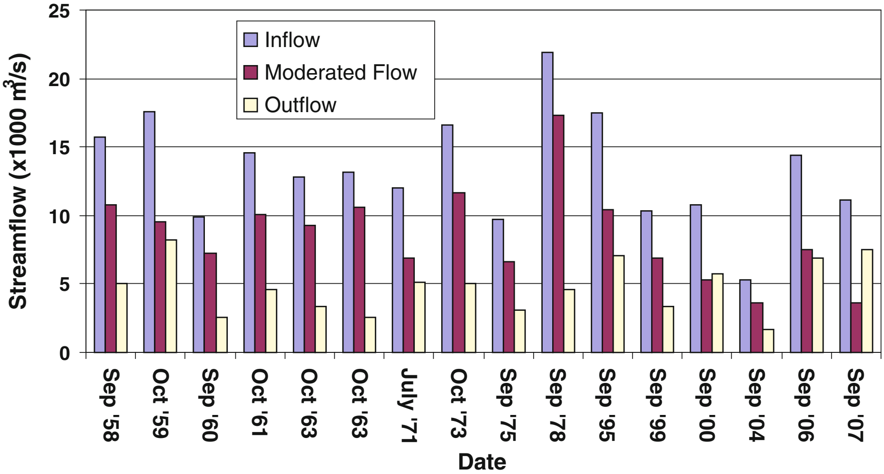

Fig. 4.10 Combined moderation by Maithon and Panchet dams during major floods. Data source: Refer to Appendix G

from the Panchet reservoir would be reduced by 80% subsequent to dam closure. According to a similar report made by Huggins and Griek (1974), the mean annual flood along the Blue river, Colorado has been reduced by nearly 40% since reservoir construction. Indeed, reduction of flood peaks by 20–75% has been widely reported by others (Lauterbach and Leder 1969; Moore 1969; Kinawy et al. 1973).

The return period of floods of different magnitudes worked out for the 24-year period (1933–1956) and 48-year period (1959–2007) shows that for the pre-dam period (1933–1956), 7,800 m^3/s is a 2-year flood, 11,095 m^3/s a 5-year flood, 13,276 m^3/s a 10-year flood, 16,032 m^3/s a 25-year flood, 18,077 m^3/s a 50-year flood, and 20,107 and 22,129 m^3/s are 100-year and 200-year floods respectively. In the post-dam period, 3,255 m^3/s is a 2-year flood, 5,258 m^3/s a 5-year flood, 6,584 m^3/s a 10-year flood, 8,260 m^3/s a 25-year flood, while 9,503, 10,737, and 11,966 m^3/s are 50-year, 100-year and 200-year floods respectively. The Damodar river peak floods during natural conditions (1933–1956) for various return

Table 4.8 Gumble extreme distribution (Type-1)

Return Period (year)	Value	
	Pre-dam	Post-dam
2	78,000.06	3,255.33
5	11,094.78	5,258.23
10	13,276.18	6,584.33
25	16,032.38	8,259.86
50	18,077.08	9,502.86
100	20,106.69	10,736.69
200	22,128.89	11,966.01

Computed by the author based on data availability shown in Appendix B and F

periods are much greater than the post-dam floods for the same return periods (Bhattacharyya 2008). This, however, does not guarantee flood recurrence strictly at those intervals as is evident from the incidence of high flood discharge above 16,992 m^3/s in the 2 years 1935 and 1941 despite the fact that 16,032 m^3/s is a 25-year flood. Similarly, in the post-dam period, high discharges of 6,522 and 6,387 m^3/s occurred in the years 1995 and 2000 although 6,584 m^3/s represents a 10-year flood within the record as a whole (Table 4.8).

When considering the magnitudes of floods of different recurrence intervals before and after dam construction, it is clear that dams have much less effect on rare events of high magnitudes (Petts and Lewin 1979). In spite of flood moderation by the DVC dams, floods occurred in 1959, 1978, 1999, 2000, 2006 and 2007, demonstrating that the lower valley is still vulnerable to sudden floods. TVA Engineer, Mr. Voorduin's project provided for the full control of a "design" flood of 28,321 m^3/s resulting from a rainstorm of 50.8 cm in the upper catchment and for the controlled flood to be limited to the assumed channel capacity of 7,080 m^3/s at Rhondia for which purpose all the dams together required a total flood reserve of 3,595.6 million m^3 (Voorduin 1947). The four dams i.e., the Tilaiya, the Maithon, the Panchet and the Konar provide total flood reserves of 1,292 million m^3. Land acquisition for the Maithon and the Panchet reservoirs up to the top of the gates is yet to be completed. When this is done the flood reserve will be 1,863 million m^3, slightly more than half of what is required for the control of the "design" flood. With this in mind, moderation of a 28,321 m^3/s design flood, or even known floods with a peak of 18,406 m^3/s to the bankfull capacity of 7,080 m^3/s, is not possible at present (DVC 1995; CWC 2001a). DVC engineers are considering alternative storage arrangements, either through acquisition of the remaining inundated land upstream of the existing reservoirs at Maithon and Panchet, or by construction of the Balpahari and the Tail pool dams at Panchet (Chaudhuri 2001, 2006).

Irrigation and power have opposing claims and their demand does always not coincide. As an example, Damodar Valley Corporation (DVC) wants to operate the dam for optimization of power benefits whereas the West Bengal Government wants more water for irrigation downstream. After the devastating flood of 1959,

Table 4.9 Guideline for combined flood release from Maithon and Panchet Dams (June–September)

Percentage of combined flood cushion occupied	Stipulated maximum combined flood release (m^3/s)
Till 20% of the combined flood reserve is occupied	1,982
While using 20–50% of the combined flood reserved	3,398
While using 50–70% of the combined flood reserved	4,531
While using 70–100% of the combined flood reserved	5,663
When 100% of the combined flood reserve is occupied, i.e. Maithon R.L reaches 495 ft (150.88 m), Panchet R.L. reaches 435 ft (132.59 m) and combined inflow is more than 5,663	Balance outflow with inflow

Table 4.10 Guideline for combined flood release from Maithon and Panchet Dams (October)

Percentage of combined flood cushion occupied	Stipulated maximum combined flood release (m^3/s)
Till 20% of the combined flood reserve is occupied	1,982
While using 20–50% of the combined flood reserved	2,265
While using 50–70% of the combined flood reserved	3,398
While using 70–100% of the combined flood reserved	4,531
When 100% of the combined flood reserve is occupied, i.e. Maithon R.L reaches 495 ft (150.88 m), Panchet R.L. reaches 435 ft (132.59 m) and combined inflow is more than 4,531	Balance outflow with inflow

Source: CWC (2001a).

the government of West Bengal requested the DVC to adopt a new water release schedule in 1961, resulting in heavy encroachment on the flood reserves of the DVC reservoirs. According to this new schedule, an outflow of 5,660 m^3/s can be released in the monsoon months (June–September) only when 70–100% of the available flood reserve, 740–1,050 million m^3, has been used up. The outflow is to be limited to 3,400 m^3/s until 50% of the flood reserve, 500 million m^3, is used and is to be increased to 4,500 m^3/s when 50–70% of the flood reserve, 500–750 million m^3, has been used up (Tables 4.9 and 4.10). In October, the outflow is regulated even more strictly (DVC 1966; CWC 2001a; Bhattacharyya 1998, 2002).

4.3 Changing Flood Behavior in the Lower Part of the Lower Damodar River

The flow regimes and channel capacities described in the previous section do not hold well for the whole stretch of the Damodar Valley, and large portions of it remain vulnerable to floods. The bankfull capacity of the Damodar River below the confluence with the Barakar decreases significantly from 7,080 m^3/s at Durgapur.

The Lower Damodar in general and the lower section of the Lower Damodar in particular, i.e. the Amta Channel along with other distributaries and Khal (Kana Nadi) has risen considerably due to siltation and encroachment on the riverbed. The actual carrying capacity of the Damodar is only 4,531 m^3/s below Durgapur and at Amta it is only 849.6 m^3/s even after resuscitation through the Lower Damodar improvement scheme. The outfall is sluiced and, as a result, its deterioration by tidal ingress has been successfully checked. The Mundeswari River can hardly carry 2,832 m^3/s; thus, any flow above 2,832 m^3/s at Durgapur can cause floods downstream (CWC 2001a). The primary consideration in the flood control strategy of the DVC dams is to provide adequate protection to the left bank embankment along the Damodar River as it protects the mining and industrial areas, important towns, as well as railways and roadways. The rural and undeveloped lower reaches of the valley, covering about 780 km^2, however, are totally neglected (Bhattacharyya Asit K 1973). The left bank has now been strengthened to withstand a controlled flow of up to 12,743 m^3/s (CWC 2001a). The inadequate capacity of the Maithon and Panchet reservoirs has necessitated high water releases during high rainfall conditions (Sen 1985a, b). The uncontrolled run-off in the catchment below dams may augment this discharge at Durgapur and Rhondia by more than 2,832 m^3/s. It must be remembered that the uncontrolled catchment area below Maithon and Panchet Dams and up to Durgapur is 2,295 km^2 and between Durgapur and the Rupnarayan river it is 2,460 km^2. This catchment itself can generate a flood intensity of 5,663 m^3/s (CWC 2001a). In the trans-Damodar distributary channels, the subsurface water yield is very high in the event of excessive rainfall. Other contributory factors to flooding include spilling of the Dwarakeswar river, flood in the Rupnarayan river as well as adverse conditions of the Hooghly river including temporary factors such as the occurrence of a high tide coming up from the Bay of Bengal (Bhattacharyya Asit K 1973; Sen 1985a; Bhattacharyya 1998, 2002).

The flood history of the Damodar during the period 1857–1917 is summarized in the EL Glass report submitted to the then Bengal Government. The results are based on observations at Raniganj, a few kilometers upstream of Durgapur (Sen 1962). Corresponding data for the pre-dam and post-dam periods at Rhondia have been given (Table 3.3). From 1857 to 1917 there were 33 floods with a magnitude between 5,664 and 8,496 m^3/s. In the later periods, this number was reduced to 11 (1933–1956) and 5 (1959–2007). Only three high floods have occurred in the post-dam period, one in October 1959, one in September–October 1978, and one in September 2007. Before dam construction, floods of the order of 10,000 m^3/s took place every 4 years and were tolerated. But after dam construction a flood as low as 2,604–3,630 m^3/s can create problems in the lower part of the lower reach of the valley due to decrease in channel capacity. At the same time, dams have provided reasonable flood protection in the upper part of the Lower Damodar valley.

Dam construction has been found to have numerous impacts on downstream channel capacity. Wolman (1967) suggested that whether channel capacity increases or decreases following dam construction depends upon the ratio of the pre-dam and post-dam discharges. In Britain, Gregory and Park (1974) have related the reduction of channel capacity to the reduced frequency of peak discharges. The overall effect of the creation of a reservoir by the construction of a dam is to lead to a reduction in downstream channel capacity (Petts and Lewin 1979; Chin et al. 2002). This is true for the Lower Damodar River as well.

4.4 Relationship Between Discharge and Rainfall in Pre-dam and Post-dam Periods

Several decades of rainfall records for the Maithon and Panchet sub-catchment have been assembled and analyzed to identify any significant changes that might have caused morphological response in the riverbed. Monthly total rainfall for the Maithon and Panchet sub-catchment has been recorded from a large number of gauges distributed throughout the Damodar river basin. Hence the mean monsoon rainfall (June–October) has been calculated simply as the arithmetic average of the gauge values. Yearly monsoon maximum and minimum rainfall has been recorded here. Maximum monsoon rainfall for the Panchet sub-catchment within the analyzed period (1892–2007) is about 1,677 mm (1984) and the minimum is about 444 mm (1972). Calculated average long-term (114 years) monsoon rainfall for the Panchet sub-catchment is about 1,134 mm. For the Maithon sub-catchment, maximum monsoon rainfall is 1,994 mm (1998) and the minimum is 467 mm (1924). Calculated average long-term (117 years) monsoon rainfall for the Maithon sub-catchment is about 1,116 mm.

Monsoon total rainfall for the Panchet and Maithon sub-catchments have been evaluated for the period from 1891 to 2007. Although there are considerable year-to-year variations in rainfall, the data does not show any significant trend that could cause systematic change in the catchment flow regimes. The spatial distribution of rainfall over the Damodar river basin, however, directly controls the spatial distribution of runoff with the highest proportion of total annual streamflow confined to the monsoon period (Figs. 4.11, 4.12).

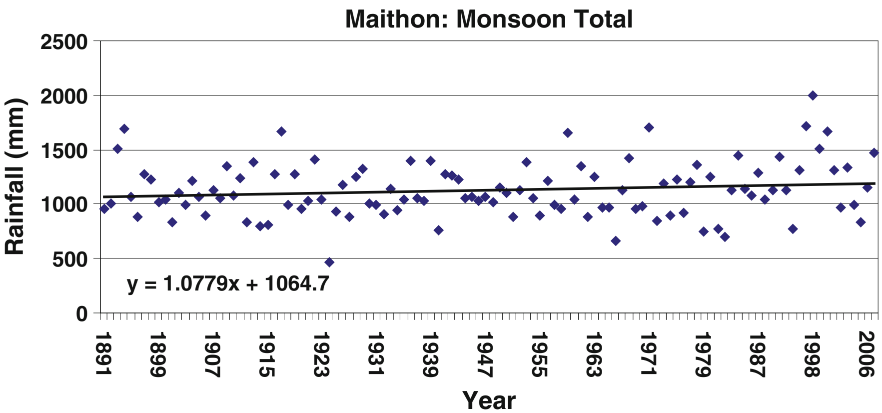

Fig. 4.11 Trend of monsoon rainfall in Damodar basin (Maithon sub-catchment)

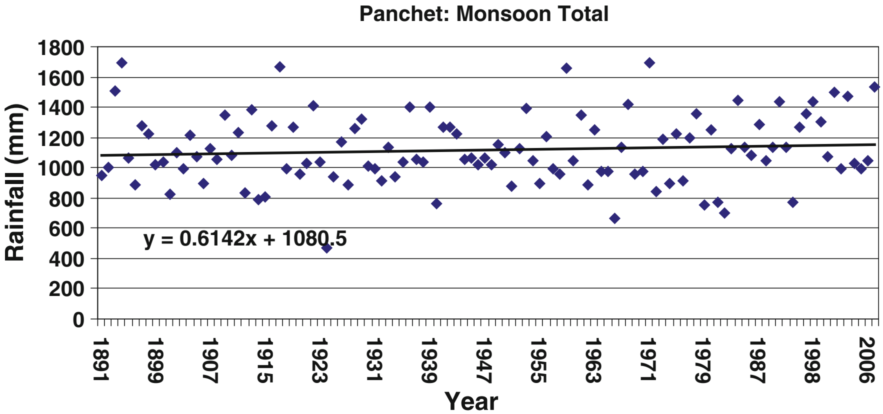

Fig. 4.12 Trend of monsoon rainfall in Damodar basin (Panchet sub-catchment)
Data Source: More than a century of rainfall data from a large number of gauges distributed within the Upper Damodar Valley, which includes the Maithon and Panchet sub-catchments, are available from MRO office of DVC, Maithon. Rainfall data for the monsoon seasons between 1891 and 2007 for both sub-catchments has been assembled and analyzed. The mean monsoon rainfall has been calculated simply as the arithmetic average of the gauge values.

Monsoon discharge was higher in the pre-dam period. Pramanick and Rao (1953) have examined rainfall data for the upper Damodar valley down to Asansol for a period of 60 years, from 1891 to 1950. According to them, high discharge at Rhondia exceeding 5,664 m^3/s on any given date was strongly correlated with the rainfall recorded on that date as well as in the preceding 2 days (Pramanick and Rao 1953; Sen 1962). Rainstorms recorded in the Damodar valley during this period produced high discharge as well as high peak streamflow from the Rhondia weir (Table 4.11). As expected, there is a strong, positive correlation between average annual discharge and rainfall (monsoon) in the Maithon and Panchet sub-catchment during both the pre-dam and post-dam periods. Thus, even in the post-dam period, high rainfall has played a significant role in enhancing discharge below control points (Bhattacharyya 1998). Although discharge at Rhondia and Durgapur is correlated with monsoon rainfall in the Maithon and Panchet sub-catchment, monsoon discharge from the dams has decreased (Table 4.3). This is because surplus monsoon rainfall is stored in reservoirs and then released to satisfy agricultural demand during the non-monsoon period. However, reservoirs are often forced to release enormous amount of water if rainfall exceeds the expected normal during a monsoon event, resulting in the inundation of large areas downstream. In fact, the breaching of embankments is an annual phenomenon in Lower Bengal. Embankments were breached in the Ajay and Damodar rivers during the 1978 floods and so-called safe areas were inundated.

Table 4.11 Relationship between rainstorms recorded at Damodar valley and high discharge at Rhondia on the Damodar

Month	Date								Total storm rainfall in mm	Date and month of occurrence, peak discharge	Magnitude of peak discharge (m^3/s)
1913 (August) Average rainfall in mm	5	6	7	8	9	10	11				
	8	36	82	108	51	24	5		314	Aug 8	18,406
1935 (August)	10	11	12	13	14	15					
	22	59	115	53	24	13			288	Aug 12	18,112
1958 (September)	14	15	16								
	18	71	79						166	Sep 16	4,682
1959 (September–October)	30	1	2	3	4	5	6	7			
	10	52	90	8	5	33	18	15	231	Oct 2	8,792
1978 (September)	26	27	28	29							
	63	97	20	4					184	Sep 27	10,919
2007 (September)	–								–	Sep 25	8,883

After Bose and Sinha (1964).

4.5 Changes in Suspended Sediment Concentration

Apart from changing a river's flood regime, dams also function as effective sediment traps. The reduction in sediment supply, combined with the change in flow regime, can affect the downstream channel substantially. Several examples can be cited that indicate a significant downstream decrease in sediment load. Williams and Wolman (1984) showed that such effects extended up to hundreds of kilometers downstream from the 21 large American structures that they examined. For the Glen Canyon Dam on the Colorado River (US Bureau of Reclamation 1976), the average annual pre-dam and post-dam suspended sediment loads as measured 150 km downstream at the Grand Canyon are as follows: pre-dam (1926–1962), 126 million megagrams; post-dam (1963–1972), 17 million megagrams with a reduction of about 87%. Similarly, on the Missouri River at Bismarck, North Dakota, 121 km downstream from the Garrison Dam, sediment loads during 1949–1952 averaged 48.6 million megagrams per year. After dam closure in 1953, the sediment load measured during 1955 was 9.8 million megagrams and during 1959 it was as reported only 5.3 million megagrams (Williams and Wolman 1984).

Data for the Damodar River also shows a significant decrease in suspended sediment concentration after dam construction. For the Lower Damodar, the average annual pre-dam and post-dam suspended sediment concentration as measured approximately 29 km downstream of Panchet at the Damodar Bridge site are as follows: pre-dam, 1.87 gr/l; post-dam, 0.54 gr/l. There is a reduction of about 72%. The average annual discharge for that period is as follows: pre-dam, 1,993.42 m^3/s, and post-dam, 2,693.72 m^3/s, showing a 35% increase in average annual discharge from the Damodar Bridge site.

Figure 4.13 shows the relationship between discharge and suspended sediment concentration of the Damodar River at the Damodar Bridge site in 1953 and 1954. Because of a lack of vegetation at the end of the dry season, the early monsoon rains result in the highest sediment load. High temperature and moisture weather the rocks and these eroded loose materials are carried along with the first half of the monsoon discharge. A study of the daily suspended sediment concentration and discharge in 1953 reveals several occasions when the peak suspended sediment concentration has taken place either one or a few days earlier than the maximum discharge. The behavior of suspended sediment concentration is different in the post-dam period due to trapping of the sediment in the reservoirs. There are several instances where such lag between the maximum values of discharge and sediment concentration is not obtained in the post-dam period (Fig. 4.13).

In the pre-dam period, average suspended sediment concentration (June–October) was higher than that of the post-dam period. In both cases the highest sediment concentration is found in the month of July. To understand precisely the relation between the suspended concentration (L) and discharge (Q), the correlation co-efficient is calculated and here the value of "r" indicates that the correlation is positive but not high. A relatively low correlation is observed post-dam because the dams act as sediment traps for the sediment received from the upper catchment (Fig. 4.14).

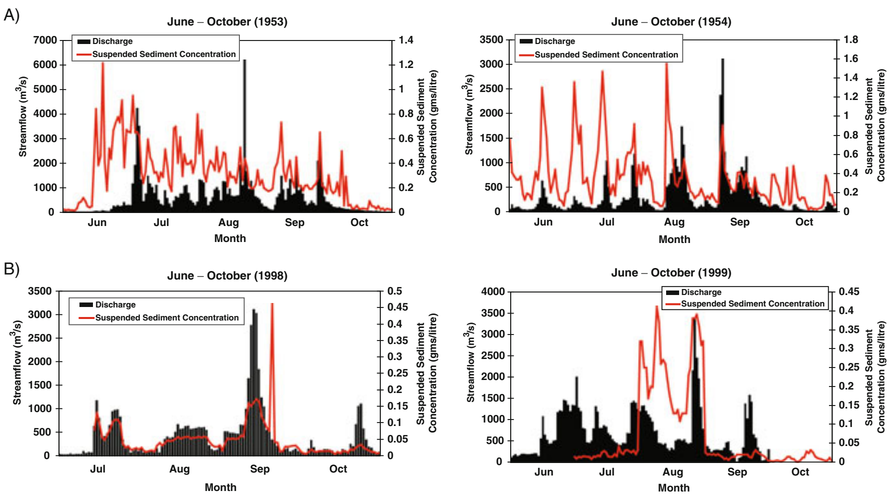

Fig. 4.13 Monsoon discharge and suspended sediment concentration at Damodar bridge sites (June to October, 1953, 1954, 1998, 1999)
The specific instances, as observed from the data, are the occurrence of highest suspended sediment concentration on 28th June of 0.9130 g/l, followed by a maximum discharge of 406.65 m^3/s on 29th June. Similarly, in July, maximum sediment concentration 0.9530 g/l on 3rd July is followed by a maximum discharge of 4,239.76 m^3/s on 5th July. Maximum sediment concentration of 0.5290 g/l on 22nd August is synchronized with the maximum discharge of 6,194.86 m^3/s on 24th August. In September, the maximum sediment concentration of 0.7350 g/l on the 10th corresponds to maximum discharge of 2,087.55 m^3/s on the 17th. In 1954 the specific instances, as observed from the data, are the occurrence of highest sediment concentration on 16th June of 1.3020 g/l followed by maximum discharge of 636.01 m^3/s on 17th June. Similarly, in July, maximum sediment concentration of 1.4687 g/l on 14th July is followed by maximum discharge of 1,048 m^3/s on 16th July. Maximum suspended sediment concentration of 1.5515 g/l on 13th August is synchronized with the maximum discharge of 516.27 m^3/s on the same date. In September, the maximum suspended sediment concentration of 0.9053 g/l on the 8th corresponds to maximum discharge of 3,107.19 m^3/s on the same day.

In 1998 the occurrence of highest sediment concentration of 0.46 g/l on 6th September corresponds with the maximum discharge of 3,113, 3,029 and 1,836 m^3/s on the 30th and 31st of August, and the 1st September respectively. Similarly, in 1999 maximum sediment concentration of 0.41 g/l on the 9th of August is associated with the maximum discharge of 1,128.75 and 1,054 m^3/s of the previous few days.
Data source: Appendix B

Data for several other dams also indicate a significant decrease in sediment load after dam construction. A clear demonstration of this effect has been given for the South Saskatchewan River in Canada by Rasid in 1979 (Goudie 1990). There has been a reduction of about 87% in sediment load after construction of the Glen Canyon Dam on the Colorado River since sediments are now trapped upstream of the dam in Lake Powell. Sediment retention is also illustrated by the case of the Nile where downstream annual sediment loads 2 years after dam closure were observed to be only 20% of pre-dam values (Hammad 1972). Until the construction

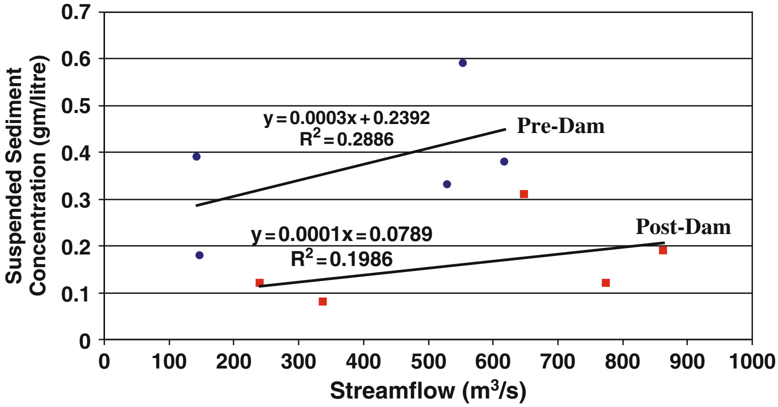

Fig. 4.14 Linear regression of average monsoon discharge and suspended sediment concentration at Damodar bridge site on the Damodar River in pre-dam and post-dam periods. Data source: Hydraulic Data Division, DVC Maithon

of the Aswan dam, late summer and autumn discharge was characterized by high silt concentration. Now the silt load is lower throughout the year and seasonal peaks have also been removed (Goudie 1990). Petts (1984) states that the Nile only transports 8% of its natural load below the Aswan High Dam. Other rivers for which data are available carry between eight and 50% of their natural suspended loads below dams (Petts 1984; Goudie 1990).

It must be noted that the data may not accurately reflect actual trap efficiency since measuring stations are at considerable distances downstream from the dams. The entrance of major tributaries, sediment supplies from the bed and banks immediately downstream from the dam, and various other factors can affect the apparent trend (Dolan et al. 1974; William and Wolman 1984). Budhu et al. (1994) recorded that sediment concentration near Lees Ferry was in excess of 10,000 parts per million (ppm) prior to dam construction but is now about 200 ppm. Prior to the construction of the Glen Canyon Dam, receding floodwaters deposited large amounts of sediment that replenished scoured bars and built new ones. In the post-dam period, only the suspended sediment load below the dam is available for bar replenishment.

The Damodar gets an enormous quantity of eroded materials from the uncontrolled catchment below the dams. There is a substantial growth of coal mining in the Ranigunj Coalfield. The coal mining-based industries, coal washeries, refractories, and significantly developed iron and steel industries in Burnpur and Durgapur have changed the whole landscape of the Lower Damodar basin into one filled with industrial smoke and coal spoils. The Durgapur-Asansol industrial belt has no perennial source of water and is served by the feeder canal of the Damodar Valley Corporation. Besides feeding the industrial complex, the canal releases water in lean months for agricultural use in neighboring districts. The only source for drawing water is the Damodar River which receives industrial pollutants through two storm water drains, the Nunia Nala in the Asansol region and the Tamla Nala in the Durgapur region.

It also receives polluted water through some drains from the Iron and Steel Co. (Burnpur), the Bengal Paper Mill (Raniganj), and the Durgapur Steel Plant (Waria). Thus the sediments and water in and around the Durgapur-Asansol region are filled with toxic chemicals. The thermal power plants contribute about 21.08,203 m^3/day (79.13% of total) of waste water discharges, the largest portion (about 92%) coming from the Durgapur power station. Fly ash constitutes the main pollutant. It has a substantial metallic toxic load, negligible non-metallic toxic load, and BOD (CPCB 1992). The river Damodar receives mine water discharge in the range of 0.2–0.5 million m^3/day. An analysis of water from several mines has indicated that majority of the mine water of this region is not acidic. It is free from toxicity and salinity (Kumar et al. 1993).

In the Damodar river 13,276 m^3/s, a 10-year flood for the pre-dam period has been reduced to 6,584 m^3/s a reduction of about a half, a 5-year flood had been reduced from 11,095 to 5,258 m^3/s and a 2-year flood from 7,800 to 3,255 m^3/s with a reduction of 53 and 58% respectively (Table 4.8). The main channel flows are no longer capable of removing sediments created by flash floods. The sediments are mostly non-compact sand and the quantity of sediment introduced from non-regulated sources exceeds the regulated capacity resulting in aggradation. The trapping of sediment and the lack of flushing due to reduction in peak discharges have inevitably transformed the Lower Damodar into an ecologically imbalanced area (Sen 1985a; Bhattacharyya 1995, 1998). The controlled release downstream from the Maithon and Panchet dams has been further depleted through irrigation intakes from the Durgapur barrage and the Rhondia Weir. In a reach beginning about 74 km downstream from the dams, this decrease in flow volume, combined with deposits from unregulated embankment-free areas and tributaries, has resulted in a river that is full of sand bars and, in many places, at an elevation higher than the adjoining

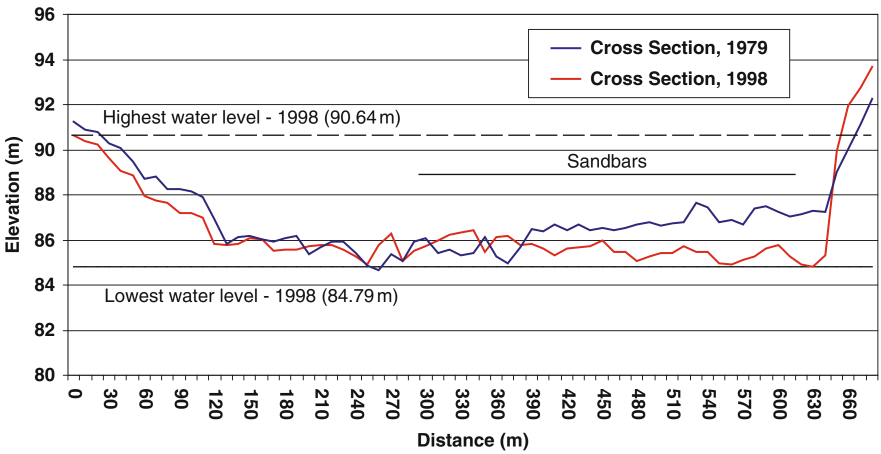

Fig. 4.15 Cross sections of the Damodar River at 36 m downstream from Damodar bridge site (surveyed on 5-9-79 & 4-23-98). Data Source: Hydraulic Data Division, DVC Maithon

land. Lawson (1925) reported similar effects downstream from the Elephant Butte Dam on the Rio Grande River. Within a decade of the closure of the structure, the channel had become choked with sediment from tributaries and the main channel was unable to transport due to reduced flow (Lawson 1925; Fiock 1931).

The contemporary riverbed of the Lower Damodar is choked with sediments below major control points. The river is full of stabilized sandbars and many transient bars are in a process of stabilization. A large portion of the sediments have been contributed by major floods in the pre-dam period, and through overland flows from embankment-free mining industrial urban areas. Even today, the Damodar continues to carry a huge sediment load during floods (Fig. 4.15).

4.6 Silting of the Reservoirs

Accumulation of sediment behind a dam is a universal phenomenon. More than half of the sediments from controlled river basins are trapped by dams and about 25–30% of sediments worldwide are intercepted by large dams if uncontrolled basins are included (Vörösmarty et al. 2003). Dendy et al. (1973) and Dendy and Bolton (1976) summarized the reservoir sedimentation data base of the United States through 1973. By relating reservoir properties to sedimentation rate, these papers have provided a guide for estimating reservoir sedimentation worldwide. Renwick (1996) summarized the database through 1975 and focused on sediment yields as related to the properties of the contributing watersheds (Stallard et al. 2001; Mixon 2002). The Stallard et al. (2001) report is based on the updated Reservoir Sedimentation Information System (RESIS) database referred to as RESIS–II. Research studies on reservoir sedimentation concluded that the deposition of stream-borne sediment causes a reduction of the storage capacity of reservoirs (Dendy et al. 1973; Dendy and Bolton 1976; Renwick 1996; Kondolf and Matthews 1993; Kondolf 1997; Stallard et al. 2001; CWC 2001b; Mixon 2002; Chaudhuri 2001, 2006; Bhattacharyya 2003).

In the Damodar upper catchment, land management and vegetal cover are poor and the rate of sediment production is far in excess of the rate assumed at the time of planning. The upper Damodar catchment is fan-shaped and conducive to a heavy concentration of floods, while the catchment downstream is a very narrow strip. The total catchment is broadly classified as 20% forest area, 50% cultivated land, 25% wasteland and 5% villages, rivers, tanks, and towns. The average annual rainfall is 1,270 mm with a range of about 760–2,030 mm (DVC 1997). The Damodar River has a drainage basin of 18,676 km^2 above Raniganj where the maximum discharge was 18,408 m^3/s in the pre-dam period (Stevenson et al. 1919). The river carried sand loads during high floods and began carrying an enormous sand load, particularly after 1830 when several collieries in the Raniganj coalfield were flourishing. Coal was known to exist in the area as early as 1774 and was worked in 1777 (Hunter 1877). Due to extensive deforestation and unscientific mining, the Damodar transported an enormous sand load during floods and formed char land or sand bars (Bhattacharyya 1998, 1999). In later periods, denuded forest and vegetal cover, poor land management, and badly eroded land prevalent in catchment areas of Maithon, Panchet (CBIP 1981), Konar (CWC 1999) and Tilaiya were responsible for high sediment yield in these reservoirs (Bhattacharyya 2003).

The sedimentation rate in Tilaiya is about 2,857 m^3/km^2/year (CWC 2001b; Bhattacharyya 2003). In the Panchet Hill reservoir, 55.5% of the dead storage space is filled with sediment. At the same time, 36.1% of the live storage space and 2.6% of the flood storage has also been lost in the 39 years up to 1995. In the Maithon reservoir, 55% dead storage space and 27.3% live storage space had been lost as of 2001. The sedimentation rate at the Panchet reservoir has fallen after the construction of the upstream reservoir at Tenughat. However, silting of the Panchet and Maithon reservoirs still has significant consequences below the reservoirs (Tables 4.12, 4.13, 4.14).

Table 4.12 Sedimentation data of Maithon reservoir (based on 2001 survey)

Storage	Initial capacity (1,000 hm)	Present capacity (1,000 hm)	Loss of capacity (1,000 hm)	Loss of capacity (%)
Dead storage up to EL 119 m	20.66	9.33	11.33	55
Live storage EL 119–125 m	60.72	44.15	16.57	27.3
Flood storage EL 125–136 m	38.23	33.38	4.85	12.6
Over all up to EL 136 m	119.61	86.85	32.76	27.4

Source: After DVC, Maithon.

Table 4.13 Rate of sedimentation in Maithon reservoir (m^3/km^2/year)

Interval in years	Number of years	Rate of sedimentation
1955–1963	8	1,524
1955–1965	10	1,429
1955–1971	16	1,333
1955–1979	24	1,238
1955–1987	32	1,290
1955–1994	39	1,280
1955–2001	46	1,132

Computed by the author.

Table 4.14 Sedimentation data of Panchet reservoir (based on 1995 survey)

Storage	Initial capacity (1,000 hm)	Present capacity (1,000 hm)	Loss of capacity (1,000 hm)	Loss of capacity (%)
Dead Storage up to EL 119 m	23.63	10.50	13.13	55.5
Live storage EL 119–125 m	25.24	16.12	9.12	36.1
Flood storage EL 125–136 m	109.30	106.38	2.91	2.6
Over all up to EL 136 m	158.16	132.99	25.17	15.9

Source: After DVC (1995), Bhattacharyya K (1999–2000, 2003).

4.6.1 The Construction of an Upstream Dam

The construction of upstream reservoirs is an extremely effective sediment control measure, especially when the sediments trapped in tanks are recovered by farmers during pre-monsoon for use as a soil additive (Morris 1995). A good example of the effect of upstream dams is cited below.

The Panchet Hill dam across the river Damodar, combined with the two upstream dams Konar and Tenughat, intersects the yield from a total catchment of 10,039 km^2. In the upper Damodar watershed, the unterraced wastelands and uplands are subject to serious sheet erosion. A great deal of destruction to the gully area is also present wherever the ground approaches a main riverbed. Vast stretches of undulating forested terrain is subject to serious sheet and gully erosion as well (DVC 1997).

Table 4.15 Decrease in rate of sedimentation in Panchet reservoir due to upstream reservoir (m^3/km^2/year)

1962	1964	1966	1974	1985	1996
1,330[1]	1,240[1]	1,050[1]	1,000[1]	670[2]	648[2]

[1]For Panchet Hill catchment including Tenughat catchment.
[2]For Panchet Hill catchment excluding Tenughat catchment.

With the construction of an upstream dam at Tenughat in 1970, sediment inflow into the Panchet Hill reservoir has been reduced (Table 4.15). It has been estimated that, up to the time of the fourth capacity survey (1974), the Tenughat reservoir intercepted about 31 million m^3 of sediment which would otherwise have moved towards the Panchet Hill reservoir. The average annual rate of deposition during the first 10-year period (1956–1966) after the construction of the Panchet Hill Dam was 10.6 million m^3. After the construction of Tenughat Dam, the average annual rate of deposition has fallen by 60% to 3.5 million m^3 in the 22-year period from 1974 to 1996. According to the sixth survey, the total available capacity of the Panchet Hill Reservoir in January 1996 was 1,358.09 million m^3 up to a reservoir level of 135.6 m above mean sea level. As the original capacity of the reservoir up to this level was 1,581 million m^3, the total volume of deposit during the past 40 years since first impounding was 222.91 million m^3. The average annual sediment deposition rate for the 22-year period from 1974 to 1996 was 648 m^3/km^2/year of catchment area (DVC 1997). It is reported that a siltation trap needs to be constructed immediately upstream of Maithon by constructing Balpahari Dam (Fig. 3.5) at about 50 km upstream of the Maithon Reservoir with catchments of 4,400 km^2, for an additional life of 58 years (Chaudhuri 2006).

4.7 Changing Channel Morphology

Because of reduced sediment load downstream from a dam, the channel pattern of a river may be changed from braided to split or single thread, and may tend to become more sinuous (Galay 1983; Williams and Wolman 1984; Andrews 1986; Everitt 1993; Kondolf and Swanson 1993; Hadley and Emmett 1998; Surian 1999). By reducing the magnitude of frequent, moderate floods, dams may lead to channel narrowing through lateral accretion (Church 1995) as riparian vegetation invades the active channel that was formerly scoured of vegetation by frequent floods (Kondolf 1997; Batalla et al. 2004). As the input conditions have been modified through setting up of control structures, the output pattern along with sediment load has changed. Streamflow below the control points has been reduced resulting in changes in channel morphology. In the Damodar River the changes in channel morphology resulted from discharge diminution and diversions for irrigation through canals. Its variation is demonstrated by the condition of meandering and braiding in a shallow alluvial channel with fluctuating regime, characterized by leptokurtic hydrograph. The cause of modification of channel pattern is the imbalance between the process of sediment transfer and energy dissipation. It represents uniquely the unstable condition of a typical tropical seasonal river flowing mostly on a low gradient sector. When a reservoir is constructed a huge quantity of sediment gets eroded and fills the low and medium flow rivers which are already saturated with sediment. The surplus material, which exceeds the carrying capacity of the flow, will deposit in the main channel, particularly in the upper part of the reach. The high flows, after unloading their burden in the reservoir, become clear and cause the downstream bed to degrade. As their ability to transport sediment is greatly reduced by changing flood regime, the amount of erosion is less than the additional accretion resulting from the non-flood season. Quite often the high flow merely shifts the previous deposits from the upper part of the reach to the lower part. In the post-dam period flood peaks have been reduced decreasing the chances of floodplains overflow. All these processes are instrumental behind the unfavorable circumstances prevailing around the downstream channel specially because of the elevated bed and the diminutive level difference between the bed and floodplain (Chien 1985).

4.7.1 Increases in the Sinuosity Index

The term “channel pattern” generally denotes the course of flow of a channel expressed in quantitative terms by the sinuosity index which is defined as the ratio of the observed length (OL) to the expected length (EL). For the sake of convenience, the Lower Damodar from the Panchet Reservoir to its confluence point at the Hooghly River has been divided into five sectors of unequal length for calculation of meandering index for different periods following Muller’s model (1968). The tortuosity of the course of a meandering stream is the outcome of both topographic and hydraulic factors. It is evident that the new channel (surveyed in 1969–1975) is more sinuous than the old one (surveyed in 1929–1930; Table 4.16).

Overall, the majority of the Damodar river system of drainage is characterized by a relatively less sinuous course. While a channel with a sinuosity index of 1.5 or more is considered meandering, the main Damodar channel is considered

Table 4.16 Sinuosity index (Mueller's model) complied from SOI maps surveyed in 1929–1930 and 1969–1975

Damodar river	Average length of bank (km)	Channel length (km)	Air length (km)	C.I	V.I	H.S.I	T.S.I	S.S.I
Bend I								
(1929–1930)	36	37	33	1.13	1.09	30.77	69.23	1.04
(1974–1975)	36	39	33	1.19	1.09	52.63	47.37	1.09
Below Damodar Barakar confluence to wooden bridge near Asansol								
Bend II								
(1929–1930)	25	28	23	1.24	1.11	54.17	45.83	1.12
(1970–1972)	23.5	27	23	1.20	1.04	80	20	1.15
Asansol to Durgapur								
Bend III								
(1929–1930)	21.16	23	21	1.18	1.05	58.33	41.67	1.07
(197–1971)	22.00	28	21	1.33	1.06	81.82	18.18	1.25
Durgapur to Rhondia Weir								
Bend IV								
(1929–1930)	34	37	29	1.26	1.16	38.46	61.54	1.09
(1969–1971)	32	40	29	1.5	1.10	71.43	28.57	1.23
Rhondia Weir to Jujuti Sluice								
Bend V								
(1929–1930)	53	56	37	1.54	1.44	18.52	81.48	1.07
(1969–1970)	52	56	37	1.53	1.43	18.87	81.83	1.07
Jujuti Sluice to Paikpara								

C.I = Channel Index; H.S.I = Hydraulic Sinuosity Index; V.I = Valley Index; T.S.I = Topographic Sinuosity Index; S.S.I = Standard Sinuosity Index.
After Bhattacharyya (1998).

marginally meandering (sinuosity index 1.30) for the whole length below the dams and remarkably straight in the upper reaches up to Barddhaman (sinuosity index 1.04). There has been a significant decrease in topographic sinuosity in the post-dam period. The standard sinuosity index shows a marked increase from the pre-dam to the post-dam period (Bhattacharyya 1998). The slope and grain size of the sediment load act as major determinants of the channel pattern. The areas of greater slope and larger grain size are generally associated with less sinuous courses whereas those of much gentler slope and finer grain size show greater sinuosity (Sen 1993).

From the SOI map surveyed in 1985–1986, a 1994 Satellite image (IRS-IBLISS-2/FCC classified image) and from 2003 LISS-3 scenes of an IRS-ID satellite, it is evident that braiding and anastomosis have also become important characteristics of this river because of the increased number and enlargement of bars between control structures. The Bara Mana is a citable example of an enlarged alluvial bar in the Lower Damodar.

4.7.2 Planform Configuration

Morphological changes along the Damodar River due to controlling include both aggradation and narrowing of channel through lateral accretion. The planform evolution of the Damodar River is illustrated (Fig. 4.16). The configuration of the river in different years has been shown in sequence. The map shows changes in the river between 1854 and 2003. Over the last several decades, the Damodar channel has undergone a general narrowing due to decreases in the flow and increased sediment supply. The channel bed has been aggraded at an alarming rate in some places, whereas the volume of sediment and rate of sedimentation has grown in other areas. Although a lot of the sediment is trapped in the reservoirs, the river still receives a million tons of sediment from the uncontrolled sectors. The capacity of the river to transport this sediment has been reduced due to the reduction of flood peaks making the channel bed a sediment sink with a series of sand bars. This effect is further enhanced due to the coarsening of bed material. In some sections the Damodar channel has been reduced due to excessive sediment deposition just after the great flood of 1978. Channel reduction appears to have been achieved by the accumulation of sediment as shoals that are now vegetated and stabilized with agricultural fields and human settlements.

There are examples of other rivers where a reduction in channel width has been observed over the years. Williams's (1978) pioneering investigations in the case of the river Platte in Nebraska were recently expanded by Murphy and Randle (2004) and Murphy et al. (2005). Williams (1978) has given a dramatic example in the case of the River Platte in Nebraska. He reported that during the nineteenth century, the river channel, which was several kilometers wide at one period, has been reduced to only 10–20% of its previous width. The Rio Grande River below the Elephant Butte Dam in New Mexico, USA was not a braided river prior to the operation of the dam. Since the Elephant Butte Dam began operations, this channel has narrowed by as much as 90% (Everitt 1993). On the Trinity River, California, construction of the Trinity Dam in 1960 reduced the 2-year flow from 450 to 9 m^3/s. Due to dramatic change in the flood regime, the encroachment of vegetation and deposition of sediment has narrowed the channel by 20–60% of its pre-dam width (Wilcock et al. 1996). Graf (2006), observed shrinkage of the entire assemblage of functional surfaces associated with the channel while studying the geomorphic effects of the hydrological change of the Great Plains and Ozark-Ouachita rivers. In the case of the Damodar river, the average width of a particular section, observed at the beginning of the twentieth century (1930), had decreased to 70% of the average width in 1854 (Fig. 4.16). The last 70 years have seen even more rapid narrowing resulting in width that is only 60% (approximately) of the initial value in 1854.

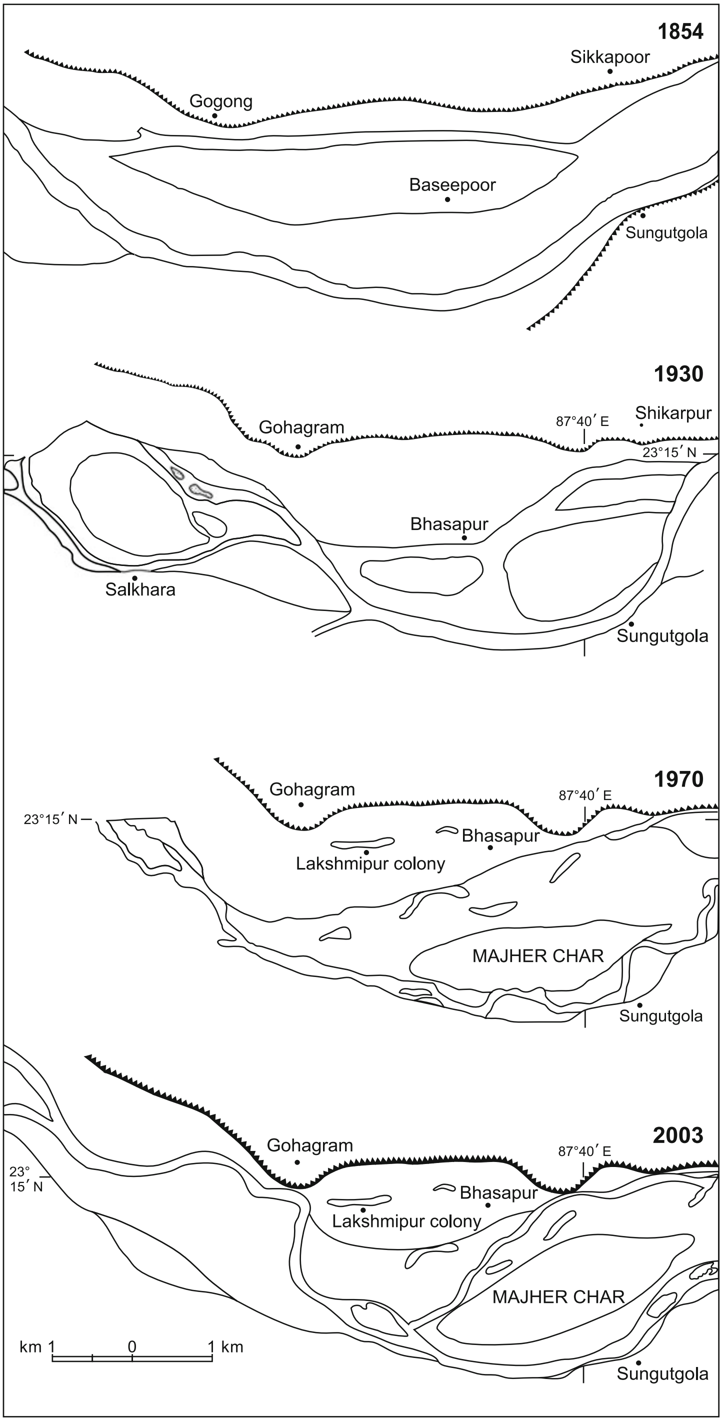

Fig. 4.16 (continued)

4.7.3 Changes in Riverbed Slope

Before the construction of dams, the long profile of the entire Damodar River could have attained a profile of equilibrium because of its pronounced erosional and depositional history since the pre-Cambrian time as is observed from the profile based on Lieut Garnault's slope data of 1864 (Saha 1944). The profile of the Lower Damodar in the post-dam situation from the Damodar Bridge site to its confluence with the River Hooghly (Fig. 4.17) shows remarkably low gradient and slight concavity with a rather inconspicuous break of profile at the bifurcation point where the main Damodar, known as the Amta channel, is bifurcated by its distributary Mundeswari. Its development can be justified by the diversion of maximum discharge into the Kanki-Mundeswari. The inconspicuous break is suggestive of the cessation of the process of sedimentation since the diversion of supply to the Mundeswari. The profile is characterized by sandbars, point bars and formation of gutter channels on a relatively wide river course, indicating the features of a misfit. The computed curve which has been drawn from the bed level elevation of 87.92 m has the lowest decremented value of slope as is evident from log a or b values. The fitness of the observed profile with the computed one drawn from Rhondia up to the outfall of Falta shows that the Yc values considerably increases in the upstream section, whereas they

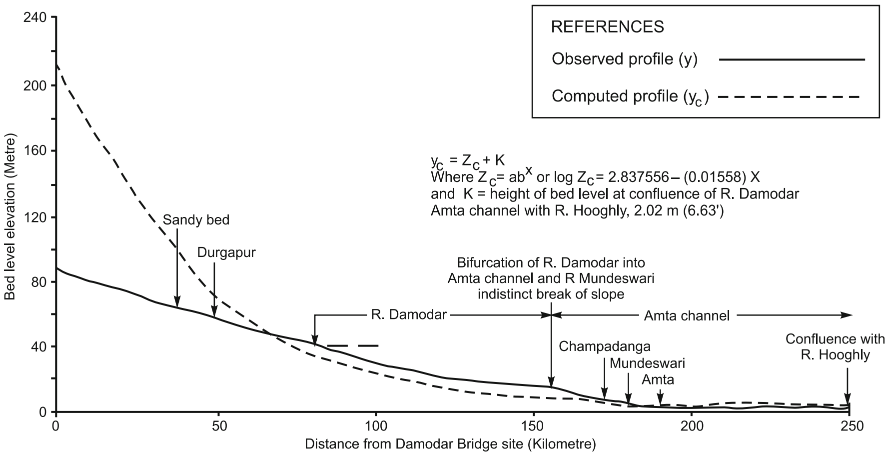

Fig. 4.17 The long profile of the Damodar river (Source: P.K. Sen)

Fig. 4.16 Planform pattern and channel changes for the Damodar River (1954–2003): changing riverbed morphology Gohagram to Sungutgola
The map shows changes in the river between 1854 and 2003.
Data source: The map drawn from the Survey of India (SOI) maps (73M/11, 12, 1: 63,360, 1: 50,000), and 2003 LISS-3 scenes of IRS-ID satellite is shown. Map of the country adjacent to the lower parts of the Damoodah and Dalkissor rivers prepared by Captain Dickens, C.H., 1854, Calcutta, at scale 1: 126,720 has been consulted

correspond very well in the lower section. The considerable variation in the upper reach speaks of a non-graded profile (Sen 1993). Construction of a reservoir in the river reduces the sediment supply downstream, and changes in the fluvial processes should tend to reduce the sediment transport capacity in order to re-establish the equilibrium. According to Mackin's (1948) concept, the slope should be flattened considerably following the dam construction and the whole process would proceed downstream at a slow rate (Mackin 1948; Chien 1985).

Another parameter studied by Sen (1978) for some cross-sections of the Damodar River is the width-to-depth ratio, a measure of the efficiency of the channel. This ratio is one of the best measures of channel conveyance characteristics. This study observed that the river channel ratio is found to have a wide range and never satisfactorily shows perfect channel efficiency. Below the Durgapur Barrage the heavy sedimentation features are conspicuous, the cross-section being of a shallow saucer shape with sandy waste and showing the formation of a number of secondary channels. Here the width-to-depth ratio mostly exceeds 40, which indicates the impotency of the channel where it is presumed to act as a sediment sink. Flushing dozes have been proposed for Damodar River (DVC V-1) but were never properly implemented due to the occupation of the riverbed by people.

4.8 Stabilization of Bars

As we have discussed in previous sections, enormous sand loads carried by the Damodar have given rise to sandbars within the river channel. It is reported that a large tract of accreted land, a few kilometers upstream of Barddhaman, was assessed and settled in 1842 (Ricketts 1853). These lands were probably formed in the devastating flood of 1840 which had a peak flow of 18,129 m^3/s at Raniganj. From the map surveyed in 1854 by Captain C. H. Dickens (1853), it is found that two sandbars had emerged a little above Barddhaman near Belkas and near Jujuti. Near Bhasapur there was a semi-transient mid-channel bar covered with grass jungle and known as *Baseepoor* (Fig. 4.16) which means it was inundation-prone. In the same period, near Jujuti and Belkas and in Gaitanpur, sandbars were semi-mobile marginal bars.

The maximum flood recorded in the pre-dam period occurred from August 6 to 12, 1913, and lasted for about 123 h. Its peak-flow of 18,408 m^3/s was observed at Raniganj. During this flood, the majority of water flowed out from the river banks and into the surrounding areas. About 4,474 m^3/s passed through the breaches in the left embankment through the town of Barddhaman and into the Hooghly River by the Banka Nadi. About 435 m^3/s went through the breaches in the left bank embankment further downstream and entered the Hooghly River near Uluberia. About 11,328 m^3/s spilled over the right bank above and below Barddhaman and found its way into the Bakshi basin of the Rupnarayan River. Only the remaining 1,416 m^3/s passed through the main channel. In such a flood the river carried enormous quantities of sand but maintained a relatively small amount of discharge. Additionally, the main river channel was unable to scour out and maintain a single adequate channel to carry the suspended sediment load. The sands were deposited along the riverbed when the current entered the flat country below Raniganj, forming a series of migratory sandbars as is evident from the map (SOI) surveyed in 1929–1930.

Increasingly, large floods were shown to modify the location and size of the sand bars along this river stretch. This can be shown from the impacts of the floods in 1935 and 1943 at Raniganj, both of which were substantially larger than the flood of 1929–1930 (Hart 1956). In 1929–1930 there were 35 migratory sandbars, all covered with xerophytic type of bushes and grasses. After the 1935 and 1943 floods, many sandbars migrated downstream, some of them merging together to form elongated bars, while others became fragmented. From the mouza maps surveyed in 1954–1957 it appears that some of the bars had acquired a definite shape. From 1947 onwards, after the partition of India and the former East Pakistan (the present Bangladesh), refugees from Bangladesh began to occupy the sand bars which have continued to be impacted by human interference to the present day. These anthropogenic landforms have acquired their present shapes and can be identified after construction of the Durgapur barrage (1958) and the Maithon (1957) and Panchet (1959) reservoirs. From the survey of Indian topographical sheets (1969–1974) it is observed that some sandbars have merged with the mainland and most of the sandbars are settled. From the topographical sheets surveyed in 1985–1986, 2003 LISS-3 scenes of an IRS-ID satellite image and 2007–2008 field survey, it is evident that some new sandbars have emerged and some have been destroyed. Formation of sandbars together with channel migration characterizes the Damodar riverbed. Today these sandbars support a population of over 50,000 people.

4.9 An Example of the Rate of Changes to the Channel Sandbars

The rate of changes to channel bar for Bara mana are shown (Table 4.17).

Table 4.17 Changes rates to channel bars

Changes in Sandbar Areas, Bara Mana (in km^2)				
1920	1957	1996	2003	Net change (1920–2003)
9.4	9.71	9.981	10.244	0.844

Rates in changes in Baramana

Period	Net change (km^2)	Rate of change (km^2/year)
1920–1957 (37 years)	0.31	0.008
1957–1996 (39 years)	0.271	0.007
1996–2003 (7 years)	0.263	0.038
1920–2003 (83 years)	0.844	0.0102

Computed by the author.

4.10 Shifting Bank Lines and Bank Erosion

Bank erosion poses a serious problem along the Damodar and its distributary channels of which Sen (1991) cites several examples. In the years between 1881 and 1956, valley side slopes at Jamalpur near the bifurcation point retreated by 94.49 and 30.48 m on the right and left bank respectively. This indicates an average rate of retreat of about 1.34 and 0.43 m/year respectively. Valley widening also occurred in different places along the Damodar River and the width of the river has increased in different places and at different rates. Shifting bank lines and bank erosion have become a problem upstream of the Durgapur barrage near Andal and between Shrirampur and Kalinagar near Barddhaman (Figs. 3.10, 3.11, 3.12). Sand quarrying from the riverbed also exacerbated the problem.

Bank erosion is also a serious problem just below the Durgapur Barrage. A series of indigenous cross-dykes or dams have been placed below the Barrage to protect the sand bars from erosion. These have generally been unsuccessful as shown in a typical example in a sandbar below the Durgapur Barrage. An indigenous cross dyke or dam exists at Rangamatia and is locally known as the Rangamatia dyke. The main purpose of this dyke is to divert the flow coming from the Durgapur barrage away from the South Rangamatia sandbar. The villagers have constructed a series of dykes afterwards to create an obstruction to flows coming through the barrage during the monsoon period. Some of these dykes were destroyed during later periods after the passing of peak flows. It is too early, however, to comment on the effects of these measures.

4.11 Present Condition of the Jamalpur Regulator

With the closure of the dead river Kana (i.e., a distributary of the Damodar) in 1863, the Jamalpur regulator was opened on the Kana Damodar in 1875. This became the only leeway for flood water on the left bank and was 4.57 m wide and 0.91 m deep. Willcocks observed that its bed height prevented it from taking low water and official regulations prevented it from taking high water. It ran for only 2 days in 1927 and 8 days in 1929 (Willcocks 1930). This ill-conceived regulator does not have any function at present (Bhattacharyya 1998).

4.12 Present Condition of Jujuti Sluice and Eden Canal

The Banka Nadi and the Damodar River are connected at Jujuti. Here a sluice and feeding channel were constructed to admit water from the parent channel to the Banka Nadi and from there to the Eden canal which was supposed to feed the Gangur, Isura and Saraswati Rivers. The design of the Eden canal, however, was inadequate for this purpose. The 1855 flood created a breach 107 m wide on the embankment of the Damodar River. The Eden canal was designed to control only as much water as the Banka Nadi was able to carry in its peak flow period (Biswas and Bardhan 1975). Initially the Banka Nadi was able to carry its run-off discharge without causing any drainage congestion in its course. Over time, however, its carrying capacity deteriorated due to the increased silting of its riverbed. This situation was worsened by the introduction of silt-laden Damodar river water to the Banka river, via the Jujuti and Jhapur sluices, for the purpose of supplying water to the Eden canal system (Sen 1976). Nothing has been done so far to remove these heavy silt deposits from the riverbed. Because the Banka Nadi would historically inundate adjacent low-lying areas during high discharge conditions, all the gates of the Jujuti sluice have been closed by sandbags, making the sluice totally inactive. Sand deposits made by the introduction of Damodar river water have also cut off the water supply to the Banka Nadi during the monsoon season.

Apart from the Jujuti sluice, many other sluices were built on the Damodar River to keep water levels well below the crest of its embankments. The surplus water during floods could be passed through these sluices and drained by several small streams to the nearby Hooghly River. This protected the whole country from inundation and supplied the parched soil with water for agriculture. This also reduced the death rate from malaria (Bannerjee 1943). All of the sluices on the left bank are now in precarious condition and sand banks have cut off the supply from the Damodar River to the left bank.

The goal of using the Eden canal for navigation remains unfulfilled. This is not surprising for several reasons. First, an environment which inhibits productive activity also inhibits movement of produce. Secondly, and more specifically, in a waterway influenced by seasonality of supply, navigation and irrigation have opposing claims. An efficient irrigation canal is supposed to run through the highest portion of the territory to be irrigated, to have a shallow depth, to collect water from the higher reaches of the river during the high water period, and to empty itself by releasing the water at a period when the general supply falls short of the requirement. On the other hand, an efficient navigation canal is supposed to run through low-lying tracts in order to gather as much water as possible during peak seasons, to have considerable depth to allow movement of boats, and to hold back the water within the canal when the general supply is small. Any attempt to combine the two is overwhelmingly likely to end in failure (Biswas and Bardhan 1975).

4.13 Present Condition of the Ulughata Sluice

Paucity of data makes it difficult to assess the Ulughata Sluice, the most recently constructed control structure on the lower part of the Lower Damodar. It has been observed, though, that whenever the Hooghly river water level rises there is a backrush of water into the Amta channel (Fig. 2.1). This has helped to revive a section of the Amta channel and the excess water is used for irrigation. Below the Ulughata Sluice, however, the channel has deteriorated noticeably to the extent that it has now been declared “a defunct channel” by the Irrigation and Waterways Department, West Bengal. The sandbars in the defunct section have become immobile and the thalweg looks like a nala (small rivulet), which at places is fordable almost throughout the year except in the monsoon season or during high tides (Bhattacharyya 1998).

4.14 Summary

The hydro-geomorphic consequences of transverse control structures on the culturally defined Lower Damodar may be summarized as follows:

i. The Jamalpur regulator no longer functions and the Jujuti sluice has been plugged with sandbags. Hence, these two control structures have lost their significance. The initial planning of the Eden canal seems to be defective as it failed to serve the twin purposes of irrigation and navigation. On the other hand, it has been connected with the DVC left bank main canal and the combined flow has revived some of the decaying distributaries of the Damodar.

ii Part of the Amta channel has been improved due to the backrush of water from the Hooghly into the channel after the construction of the Ulughata sluice. Below the Ulughata sluice, the channel appears to be a defunct one.

iii Monsoon discharge below the Durgapur barrage and the Rhondia weir has decreased but there is more release of water during the non-monsoon period for irrigation purposes.

iv. Frequency and magnitude of peak flow have decreased and the peak discharge has shifted from July–August to late September–October.

v. Return period of flood of bankfull capacity has increased from 2-year in the pre-dam to 14-year in the post-dam period. In the river, 13,276 m^3/s, a 10-year flood for the pre-dam period, has been reduced to 6,584 m^3/s flood, a reduction of about a half, a 5-year flood has been reduced from 11,095 to 5,258 m^3/s and a 2-year flood from 7,800 to 3,255 m^3/s with a reduction of 53 and 58% respectively.

vi. Under very high rainfall conditions the Panchet and the Maithon Dams are forced to release excess water. This creates drainage congestion in the lowermost part of the Damodar when the ground water table rises significantly in excess rainfall years.

vii. From 1857 to 1917 there were 33 floods with a magnitude between 5,664 and 8,496 m^3/s. In the later periods, this number was reduced to 11 (1933–1956) and 5 (1959–2007). The number of floods with a magnitude between 2,472 and 5,664 m^3/s has increased from 4 in the pre-dam period to 25 in the post-dam period (Table 3.3).

viii. In the pre-dam period the suspended load was higher than that of the post-dam period. The relation between suspended load and discharge is positive but not high due to trapping of sediments in the reservoirs.

ix. The riverbed is characterized by sandbars, point bars and gutter channels. Near the bifurcation point, there is a reverse slope. Alluvial bars are less transient now.

x. Sinuosity index has increased. Channel length has increased due to the increased sinuosity index. Shifting of bank lines and bank erosion are observed mainly on the left bank side.

Landforms and associated processes are genetically classified as endogentic and exogentic. River control structures, major or minor, are anthropogenic landforms now acknowledged as belonging to the genera of exogenetic landforms. The status and designation of geomorphic forms, processes, and materials that have undergone changes due to these anthropogenic interventions in a fluvial system are really unknown even now. Stream flow, riverbed sedimentation, bank erosion and similar processes are always governed by universal physical laws or natural laws. Humans as geological agents can only modify the flow pattern by controlled release of water from a reservoir but the stream flow itself, whether laminar or trubulent, is controlled by a fluid mechanism. Similarly, humans can accelerate or reduce sedimentation and even change the locale of this process by deliberate attempts but cannot change the principles of vertical and/or lateral accretion. Critical tractive force, stream competence, and capacity are all controlled by physical laws. The same physical laws operate in a natural as well as in a reservoir channel and the river control structures cannot change them. As noted by Leopold et al. (1964), geomorphic effects produced by humans are, as a rule, the same as those produced without human intervention. The human role is generally to modify some variables in the system.

Although products of economic and social demands, river control structures have profound influence on the flow regime alteration, channel modification and riverbed sedimentation (Williams and Wolman 1984; Church 1995; Bhattacharyya 1998, 2009; Graf 2006; Grantham et al. 2008). In the case of the Lower Damodar, flow regime, flood behavior, and channel morphology has changed remarkably, particularly within few decades of dam closure, and these changes have followed hydro-geomorphic principles as well as economic and social principles.

The foregoing analysis shows that geomorphic forms and processes should be placed in a separate category in the genetic and/or generic classifications of forms and processes. They should be designated as "quasi-natural" forms and processes. They are natural, as they follow natural laws, but they have been modified by human-made structures and human action; therefore, they are quasi-natural and human-modified in character (Bhattacharyya 1998).

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