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Downstream Decreasing Channel Capacity of a Monsoon-dominated Bengal Basin River: A Case Study of Dwarkeswar River, Eastern India

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Abstract: Downstream changes in channel morphology and flow over the ephemeral Dwarkeswar River in the western part of the Bengal Basin, eastren India were investigated. The river stretches from the Proterozoic Granite Gneiss Complex to the recent Holocene alluvium, forming three distinctive geomorphological regions across the river basin: the pediplane and upper and lower alluvial areas. Sixty cross-sections from throughout the main trunk stream were surveyed and the bankfull width, depth, cross-sectional area, and maximum depth were measured. Sediment samples from each location were studied and the flow velocity, stream power, Manning's roughness coefficient, and shear stress were estimated. The results show that the bankfull channel cross-section area, width, width-to-depth ratio, and channel capacity increased between the beginning and middle of the river. Thereafter, the size of the river started to decrease in the lower alluvial area. This was characterized by gentle gradients, cohesive bank materials with grass cover, and channel switching. Within the lower part of the river, the channel capacity was observed to diminish as the drainage area increased. This increased the bankfull flow frequency and accelerated large floodwater losses in the floodplain via overbank flows and floodways.

Keywords: bankfull channel width; bankfull discharge; Dwarkeswar River; flat alluvial plain; channel degradation; overbank flow and flood

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1 Introduction

Downstream channel morphology variation is significant to flood control. It affects hydrographs, flood plains, reservoirs, and construction of various engineering works. It can also affect the local economy (Chin et al., 2002). The systematic channel morphology, e.g., the channel width, mean flow depth, mean flow velocity, and discharge variations has been termed 'hydraulic geometry' by Leopold and Maddock (1953). The channel morphology and flood plains result from the sedimentological character, climatic condition, flow behaviour, tectonics, topographic setting, and nature of flood plain vegetation (Kemp, 2010). Various scholars, such as Knighton (1999), Park (1977), Pitlick and Cress (2002), Gugliotta et al. (2019a; 2019b), Lee et al. (2019) and Pfeiffer et al. (2017) have investigated various aspects of downstream changes in hydraulic parameters. Most of these researchers have found that the bankfull channel cross-sectional area, width, depth, and discharge increase in the downward direction of a river (Schumm, 1960; Knighton and Wharton, 1998; Pfeiffer et al., 2017; Lee et al., 2019). This has also been observed in ephemeral rivers with various flow rates (Leopold and Miller, 1962; Leopold et al., 1964; Park, 1977; Wolman and Gerson, 1978; Kale and Gupta, 2001; Yaraghi et al.,

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Downstream increases in channel capacity, width, and discharge are well established in these studies. In addition, downstream channel dimension decreases have been reported since the 1980s on some rivers. These include large rivers in arid zones associated with low-gradient floodplains (Tooth, 2000), semiarid and low-gradient anabranching rivers (Kemp, 2010), ephemeral channels in hyper-arid areas with low sea levels (Bowman et al., 2010), mountain rivers with sediment size to stream power ratios below 10 000 kg/s^3 (Wohl, 2004), and rural river basins (Nanson and Young, 1981). In addition, moderate sand-bed rivers were not presented sufficiently in the international literature (Kemp, 2010). This may be because of poor accessibility to lowlands and large sandy channels (Kemp, 2010).

This study focused on the east-flowing rivers of the western part of the Bengal Basin, India. These rivers arise from the Chhotanagpur Plateau and join with the Bhagirathi River, which is located primarily in the western part of West Bengal. This region is characterized by intensive agricultural activity and a dense population (Bandyopadhyay et al., 2014). In addition, the lower portions of the east-flowing rivers of West Bengal are characterized by poor drainage conditions and frequent flooding (DoIW-GoWB, 2014, 2015, 2016; Chapman and Rudra, 2015; Irrigation & Waterways Department, 2016). Frequent floods have repeatedly affected moderately (1000 person/km^2) to densely (more than 2500 person/km^2) populated areas (Census of India, 2011; Bandyopadhyay et al., 2014). Although several measures have been taken to control these scenarios since independence, the people of these areas continue to suffer from flooding and waterlogged conditions (DoIW-GoWB, 2014, 2015, 2018; Chapman and Rudra, 2015). According to Nath et al. (2008), heavy rainfall is the main cause of floods in this region. In addition, it is known that if the available discharge exceeds the bankfull channel capacity of a river, water can spill from the channel to surrounding areas and can result in flooding. Thus, the bankfull channel plays an important role in generating floods. And, several regional studies have casually stated that the channel morphology decreases in this low-lying alluvial plain mainly primarily due to anthropogenic reasons (Chakrabarti, 1985; Sen, 1985; Mukhopadhyay, 2010; Let and Pal, 2011; Roy, 2012; Ghosh and Guchhait, 2014). However, anthropological activities became apparent only after 1950 (Bandyopadhyay et al., 2014). This leads us to question the role of such activities, as overall river channel morphology trends have been consistent from 1920 to the present. Furthermore, there is a lack of intensive study of this subject. Therefore, the objective of this study was to understand the morphological characters of these rivers. This study focused on the Dwarkeswar River of West Bengal, which is an east-flowing river in the western part of the Bengal Basin and lies primarily in West Bengal, India (Fig. 1). The lower basin of this river is flooded every year. The area has a population density of 1500 to 2000 people/km^2 (Census of India, 2011), which is higher than the mouths of other rivers in this area. In the 1920s, only 19.1 km (8.35%) of earthen embankment had been constructed along the main river (SOI, 1925). This had been increased to 62.84 km (27.48%) after 2000 (SOI, 1925; 1978). This indicates the recent dominance of anthropogenic interventions and is part of the reason for selecting this river basin. To fulfil our objective, downstream morphological and hydrological changes based on physiographic divisions were measured via a field survey using a dumpy level along a 228.65 km stretch of the Dwarkeswar River. This study analysed channel morphology trends based on physiographic divisions and explored relationships between channel morphology, flooding, and relevant root causes and would help to reduce flood damage and to prepare sustainable development plans for the area.

2 Materials and Methods

2.1 Study area

The east flowing rivers of the western part of the Bengal Basin originate from the granite gneiss-dominated plateau of the western part of West Bengal and meet with the Bhagirathi River. The lower parts of these rivers experience floods every year (DoIW-GoWB, 2014; 2015; 2018) (Fig. 1). The Dwarkeswar River is also known as the Dhalkishore River (SOI, 1978), and is a major river in the western part of West Bengal (O'Malley, 1912). The basin area of this river is enclosed between latitudes 23º32′00″N, 23º40′25″N and longitudes 86º31′08″E, 87º47′58″E (SOI, 1978) (Fig. 1). The Dwarkeswar River originates from the Rarh region near Tilboni Hill in Chhotanagpur Plateau, Purulia District and eventually joins with the Shilabati River at

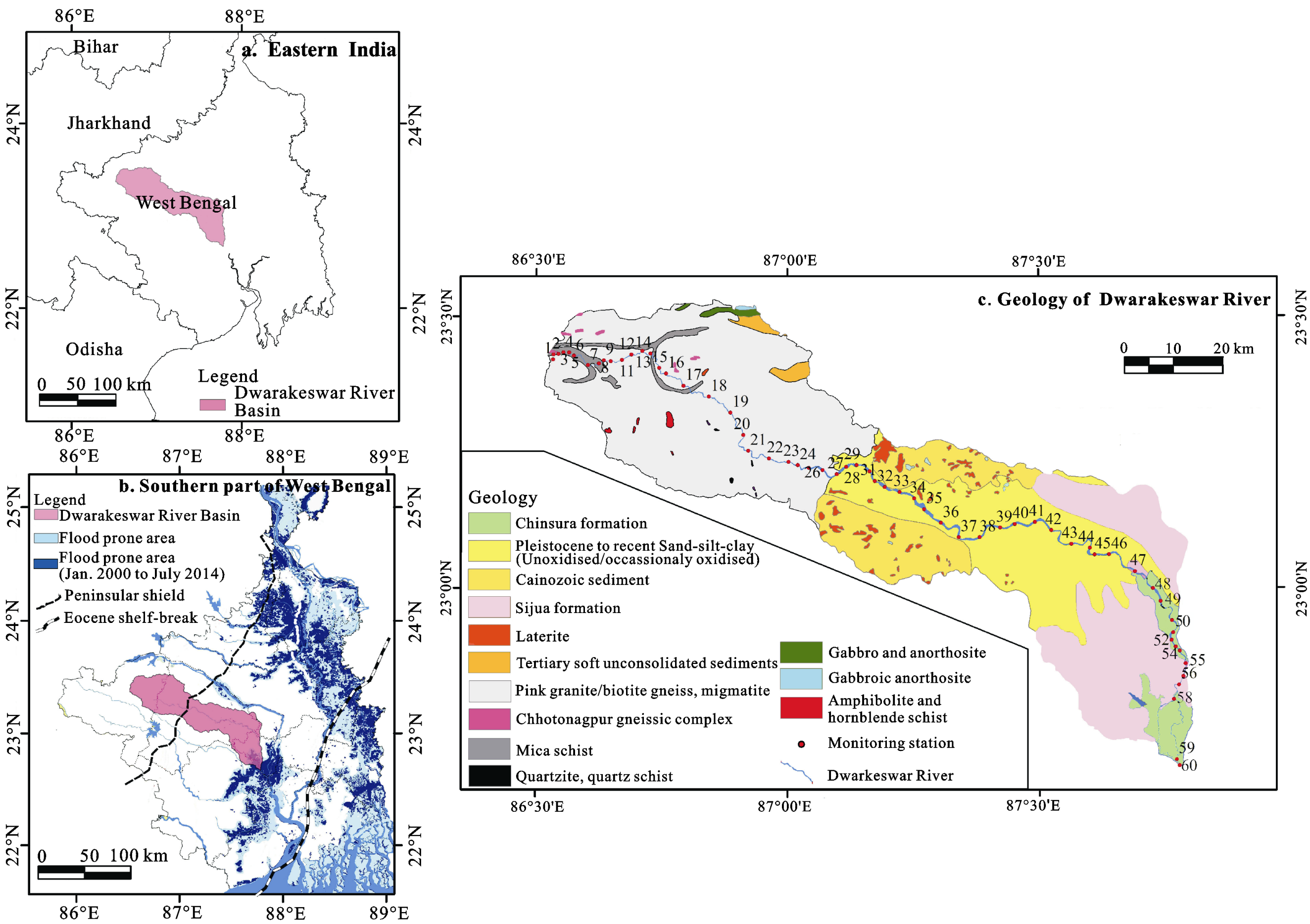


Fig. 1 Map of the study area: (a) administrative location of the Dwarkeswar River, India, (b) flood-prone areas, areas affected by the 2016 West Bengal floods (ISRO, 2018), and (c) the of surface geology study area (GSI, 2002)

Bandar near Ghatal Town in Paschim Medinipur District (also known as Rupnarayan) (O'Malley, 1912; Bhattacharya et al., 1985). The total length of the stream is 228.65 km and it occupies 4356.6 km^2 of West Bengal (SOI, 1978). The maximum basin width and length are 40.80 km and 151.51 km, respectively. The regional elevation ranges between 438 m and 10 m (SOI, 1978). Susuniya Pahar (438 m) and Tilabani Hills (407 m) are classic examples of residual hills or monadnocks (Rudra, 2009) in the area. Existing literature indicates that this region was covered with dense tropical deciduous forest during the 17th century. This included *Sal* (*Shorea robusta*) climax vegetation. The region was known as '*Jangal Mahal*' during British rule (Hunter, 1877, 1883; Schlich, 1885; Biswas, 1976; Siddique, 1996; West Bengal Pollution Control Board, 2017). Presently, only 11.56% area of the basin area is under forest cover (ISRO, 2018).

The Dwarkeswar River is a sixth-order stream with a bifurcation ratio that ranges from 3.00 to 5.67 (Table 1). The total basin relief is 428 m. However, the trunk stream has an overall altitude decrease of only 248 m. (SOI, 1978). The Gandheswari, Futuari, Darubhanga, Dudhbhaiya, Arkasha, Dangra, and Beko are the major tributaries of this river. The associated agricultural area occupies nearly 67.5% of the drainage basin (ISRO, 2018). Most sediment and water that flow to the river are supplied by its bare, deforested pediplane area. Bedload proportions and suspended sediment load records are absent, but the river is typically dominated by muddy flow with a bed load of fine gravel and sand. The Dwarkeswar Basin exhibits two distinctive climatic characters: a semi-arid climate in the upper part and a hot, humid climate in the lower part of the basin (NBSS&LUP, 1990). The average annual rainfall increases from less than 1300 mm at the top of the basin to 1500 mm at the lower part (Hunter, 1877; Mishra, 1994; Bandyopadhyay et al., 2014; IMD, 2018). Most rainfall (>75%) occurs within June, July, August, and September. Flash floods have become common during the peak monsoon (Bandyopadhyay et al., 2014; Rudra, 2014). The annual potential evapotranspiration in the pediplane area of the basin (above 1600 mm) exceeds the total precipitation (Rudra, 2009), resulting in strong seasonal flow during the monsoon period and dryness in the summer. The average estimated flow of this river is quite low: 2.8 m^3/s in November, 39.2 m^3/s in February, 80.3 m^3/s in May, and 335.8 m^3/s in August (West Bengal Pollution Control Board, WBPCB, 2017). There are three gauge stations on the Dwarkeswar River: one is near Bankura Town in Bankura District, another is in Arambag Town, and the third is in Shakepur within Hooghly District. However, these record only the gauge height of the river. Historical records of the river gauge height near Arambag station from 1978 show that the highest recorded flood was 7.71 m above the bed (DoIW-GoWB, 2014). In addition, sand mining has significantly increased the channel depth in a few sections of the river.

2.2 Channel morphological parameters

The channel morphology of 60 monitoring stations of the entire Dwarkeswar river (Fig.1c) was investigated in December 2018 by deriving its morphological parameters using a Sokkia C410 auto-level and Garmin eTrex 20 GPS. The standard VDFW (Vermont Department of Fish and Wildlife, 2009) protocols were followed. The World Geodetic System (WGS) 1984 UTM Zone 45 North projection system and WGS 1984 datum were used in this study. Topographical maps (73N/ 5, 9, 10, 13, 14, 73I/ 10, 11, 12, 14, 15, 16, 73M/ 4, 7, 8, 12, 13, and 16) published by the Survey of India at 1 : 50 000 scale were used to determine the stream order, stream length, and drainage area, as well as to understand the geomorphic situation in the area.

Table 1 Drainage network properties of Dwarkeswar River, India

Stream order	Number of streams	Stream length (km)	Bifurcation ratio	Basin area (km^2)
1	1073	1.11		4.35
2	280	2.19	3.83	9.43
3	62	6.56	4.52	34.65
4	17	14.30	3.65	116.17
5	3	31.07	5.67	694.28
6	1	152.19	3.00	4356.72

Note: Data from Topographical Maps published by Survey of India (SOI), 1978

The channel width, cross-sectional area, and maximum depth were measured based on the bankfull stage (Fig. 2). Mean depths were estimated by dividing the bankfull channel cross-sectional area by the bankfull width. The marked break in slope between the floodplain and channel, nature of vegetation, average channel bank height through the reach, channel width from topographical maps, and sediment texture and colour were used to identify the bankfull stages in this study. Longitudinal profiles of the river and bed slopes of each reach were calculated from cross-sections.

$$\text{Mean width} = (\text{Bankfull channel cross} - \text{section area} \,/\, \text{Bankfull width}) \quad (1)$$

In this study, the Manning roughness (n) was determined using the method provided by Chow (1959) via the following equation

$$1-n = (n_0 + n_1 + n_2 + n_3 + n_4) \times m \quad (2)$$

where n represents the Manning roughness; n_0 indicates the base n value; $n_1 + n_2 + n_3 + n_4$ represents adjustments for roughness factors such as the degree of irregularity (n_1), variation in channel cross-section (n_2), effect of obstructions (n_3), and degree of vegetation (n_4); and m is an adjustment for the meandering nature of the river in a particular section.

In addition, the bankfull velocity (v) (m/s) and its associated discharge (m^3/s) were calculated using the Manning coefficient (n) (Equ. 2) (Chow, 1959).

$$v = (1/n)\ R^{2/3}\ s^{1/2} \quad (3)$$

$$Q = (v \times a) \quad (4)$$

where v is the velocity (m/s), n is the manning roughness coefficient, R is the hydraulic radius (m), s is the

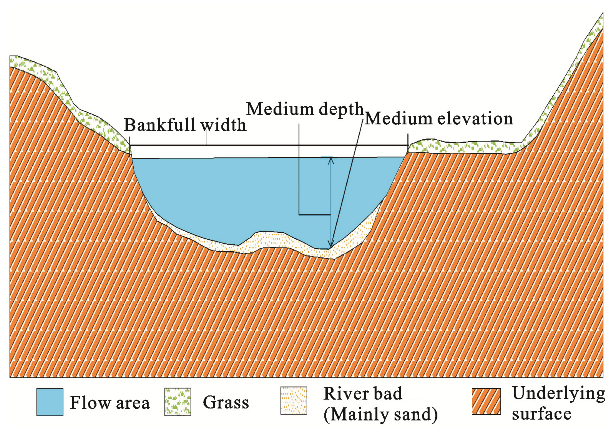


Fig. 2 Schematic representation of various channel parameters

channel slope (m/km), Q is the discharge rate (m^3/s), and a is the channel cross-sectional area (m^2).

Based on the discharge, the shear stress (τ_0) (N/m^2) and unit stream power (ω) (W/m^2) at various stations were estimated using Equs. 2, 3, and 4 (Shepherd et al., 2011).

$$\tau_0 = \gamma_w \times Rs \quad (5)$$

where τ_0 is the shear stress (N/m^2) and γ_w is the specific weight of water.

$$\omega = \gamma_w \times Q \times s/w \quad (6)$$

where ω is the unit stream power (W/m^2), w is the channel width and Q is the discharge rate (m^3/s).

The width-to-depth ratio of the channel was also calculated. It was defined as the ratio between the bankfull width and the mean depth in a given cross-section. It was one of the key indicators used to understand the distribution of available river energy and ability to move sediment in a particular channel. The statistical description of various properties were shown in Table 2.

2.2.1 Grain size analysis

Grain size analysis is an important source of information regarding the sediment type, sediment texture, nature of flow, and nature of deposition. Sixty sediment samples were collected from each site. The surrounding vegetation and vegetation root depth near the sample locations were considered during sample collection, as were local disturbances (Ford et al., 2016; Lutz et al., 2008). The sediment samples were analyzed and mean grain sizes determined using the method by (Folk and Ward, 1957). Sediment samples were classified into eight classes following Wentworth (1922). The classes were fine grains, granules, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, and coarse silt. After collecting this data, analyses were performed to understand the nature of the downstream channel morphology of the river.

2.2.2 Sinuosity index

The sinuosity index (SI) is a dimensionless index that can indicate tectonic activity in the channel reach. It is calculated to detect the degree of distortion based on the work of Friend and Sinha (1993).

$$SI = L_{cmax} / LR \quad (7)$$

where LR is the length of the channel bed and L_{cmax} is the mid-channel length of the same reach. The sinuosity index can be classified into five categories: straight (< 1.05), sinuous (> 1.05), meandering (> 1.50), braided (> 1.30), and anastomosing (> 2.00) (Morisawa and Clayton, 1985).

2.3 Drainage basin zonation

Based on the Geological Survey of India (GSI: Geological Survey of India, 2002), Bandyopadhyay et al. (2014), and a report from the West Bengal Pollution Control Board (2017), the entire basin area was classified into three portions (Figs. 3a, 3b, and 4). These were the pediplane area (more than 75 m from mean sea level (MSL)), the upper alluvium area (75 m to 22 m from MSL), and the lower alluvium area (less than 22 m from MSL) (Figs. 1c, 3a, and 4).

Table 2 Statistical description of various channel properties of Dwarkeswar River, India

Variables	Pediplane area		Upper alluvial plain		Lower alluvial plain	
	Mean	Std. deviation	Mean	Std. deviation	Mean	Std. deviation
Drainage area (km^2) (A)	54314	55231	244301	43607	361163	36650
Bankfull width (m) (W_{bf})	148	115	460	96	193	95
Bankfull max depth (m) (D_{max})	3.58	1.77	5.07	0.88	6.43	1.20
Bankfull mean depth (m) (D_{bf})	2.57	1.21	3.27	0.66	4.58	0.82
Width/depth ratio (W/D)	58.11	39.80	147.62	52.15	43.85	26.77
Bankfull flow area (m^2) (A_{bf})	446	411	1485	326	886	436
Slope of the reach (m/m) (S)	0.0014	0.0008	0.0006	0.0001	0.0004	0.0001
Flow (m^3/s) (Q_{bf})	486	459	1489	351	970	549
Shear stress (tau) (N/m^2) (τ_0)	24.36	8.55	16.97	4.26	16.91	5.60
Stream power (W/m^2) (ω)	31.46	22.33	17.72	5.81	18.73	7.38
D50 (μm)	1436	614	628	328	330	69
SI	1.22	0.14	1.26	0.24	1.23	0.15
N	N = 28		N = 19		N = 13	

Notes: D50 results shows the size of 50% sediment particles is smaller than the result and SI indicates the Sinuosity Index

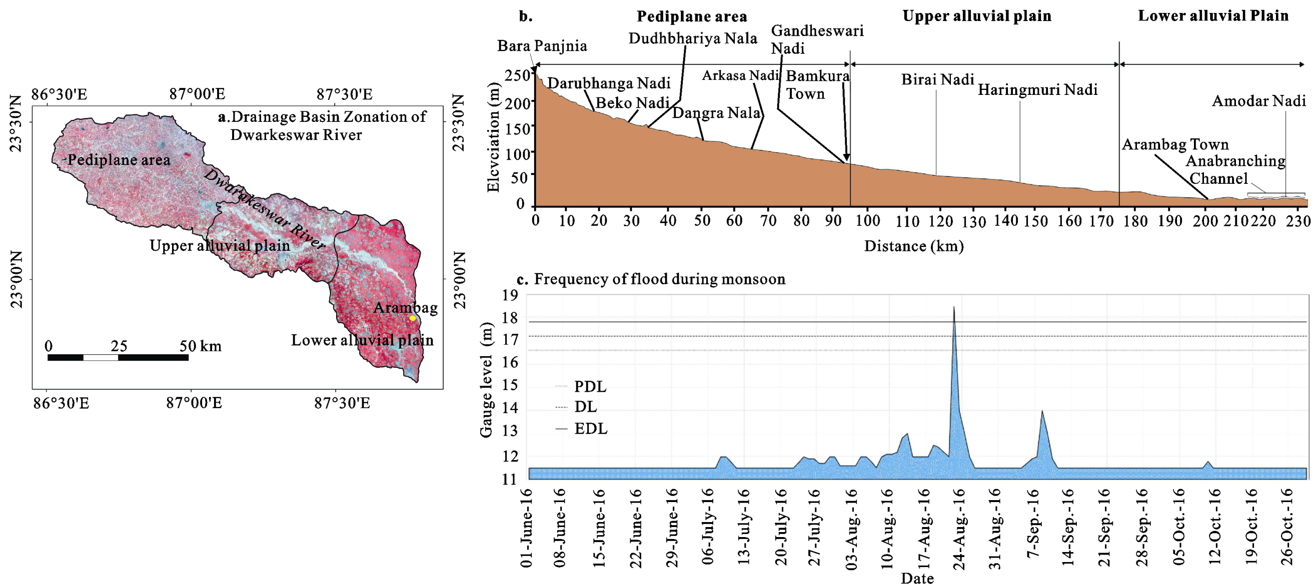


Fig. 3 Zonation of the Dwarkeswar River basin of India superimposed over a standard false colour composite (FCC) derived from Landsat 8 data (a), the long profile of the Dwarkeswar River and its associated geomorphic divisions (b), and the temporal distribution of the monsoon period river gauge height (c), as recorded near Arambag station in Hooghly, where PDL is primary danger level (16.61 m), DL is danger level (17.22 m) and EDL is extremely danger level (17.83 m) (modified from Malik and Pal, 2019a and DoIW-GoWB, 2018)

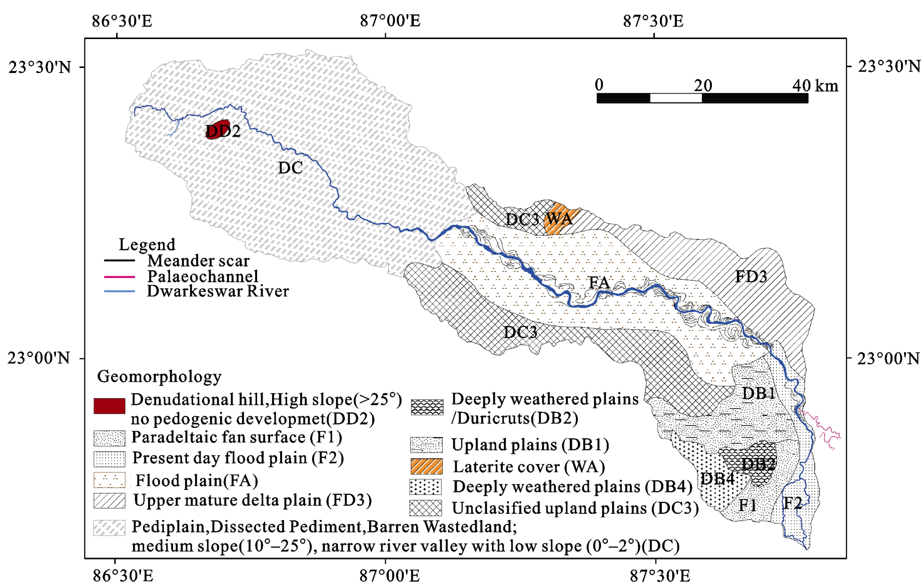


Fig. 4 Geomorphological map of the Dwarkeswar River basin, India

2.3.1 Pediplane area

The pediplane part of this basin is part of the extended portion of the Chhotanagpur plateau (GSI, 2002). It was characterized by a Chhotanagpur Granite Gneiss complex of Proterozoic age, a few patches of tertiary soft unconsolidated sediments, and mica schist (GSI, 2002) (Figs. 1c and 4). Undulation and a rolling surface topography with scattered residual hills of hard rock, which sometimes lacked vegetation (SOI, 1978), were among the distinct characteristics of this region. The channel in this region flowed over the pediplane area, but channel water rarely spilled over into the main course of the river. The bankfull channel width could easily be identified via a sharp change in the valley slope. The channel slope was quite high in this area when compared to the rest of the basin. The channel depth was also quite high, reaching 3.5 m in some areas. The channel pattern in this area varied from straight to sinuous. The riverbank slope was particularly high and devoid of vegetation cover.

2.3.2 Upper alluvial plain

The geology of the upper alluvium part of the basin belonged to the Cainozoic and Pleistocene ages. The largest portion of this area was associated with older alluvial plains, although some lateritic patches could be found within this region (GSI: Geological Survey of India, 2002). In addition, wide, curved valleys and spurs dissected in a transverse manner by the Dwarkeswar River could be observed within this area. Another dominant feature of this region was lateritic tracts with numerous rills and gullies formed by ephemeral 1st, 2nd, and 3rd order river tributaries (WBPCB, 2017). In this section of the river basin, the riverbed was characterized by a large, flat sand bed and high bankfull width. The riverbed was particularly deep in this area because of sand mining activity. The valley side and channel slopes were particularly low. The width-to-depth ratio in this section of the river was quite high. A meandering channel pattern was observed throughout the river. Several meander scars were found in this area beside the active course of the river.

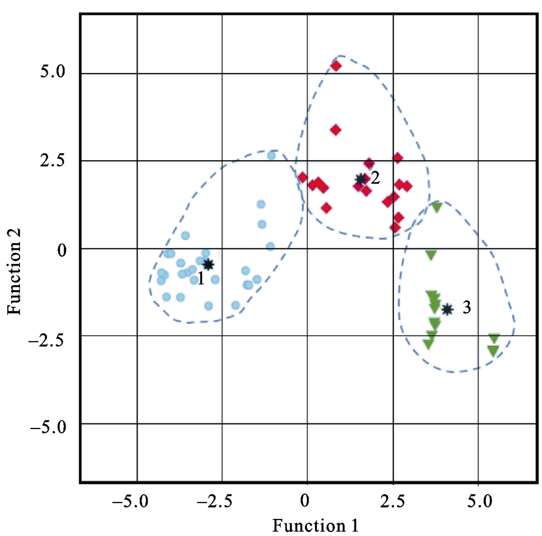
2.3.3 Lower alluvial plain

The lower alluvium area lay along the world's largest delta, the Ganga-Brahmaputra Delta. This delta is part of the western part of Bengal Basin (Roy and Chatterjee, 2015), which is a structural depression filled by the Ganga and Brahmaputra River systems (Kuehl et al., 2005; Bandyopadhyay, 2007; Steckler et al., 2008; West Bengal Pollution Control Board, 2017). During this study, the river was sluggish with a vast flood plain and gentle slope. Agriculture was the most prominent activity in this area. The bankfull width of the river in this section could be derived easily as the valley side slope was quite high. The bankfull maximum and mean depths were also quite high. The width-to-depth ratio and slope of the channel cross-section in this area were lower than those of the pediplane and upper alluvial river basin zones (Figs. 3a, 3b, and 4). A temporal distribution of the Dwarkeswar River gauge height near Arambag station is shown in Fig. 3c, and indicates that the river exhibits sudden flow changes (Malik and Pal, 2019b).

2.3.4 Canonical discriminant analysis

Canonical discriminant analysis (CDA) was employed to justify river basin classifications (Fig. 5), as it helps to communicate between-group variation by developing a linear combination that allows the reaches of interest to be differentiated successfully (Dunteman, 1984; Norusis, 1985; Roy and Sahu, 2016). The distinctive geomorphic characters of the three sub-regions were processed using CDA to justify the classifications statistically.

The overall analysis indicated that there were significant differences (Fig. 5) between the pediplane, upper alluvial plain, and lower alluvial plain areas. Significant differences were observed among the variables associated with various parts of the basin. However, differences



Classification results					
		Predicted group membership			Total
	Region	1	2	3	
Original court	1	27	1	0	28
	2	0	18	0	18
	3	0	1	12	13
Predicted (%)	1	96.4	3.6	0	100
	2	0	100.0	0	100
	3	0	7.7	92.3	100
96.6% of original grouped cases correctly classified					

Fig. 5 The quality of drainage basin classification based on Canonical discriminant analysis (CDA) analysis

in the sinuosity index (*SI*) were negligible (P= 0.635) and differences in the shear stress were small (P = 0.008) among these three sub-regions of the basin. The classification report showed that 96.4% of the pediplane area, 100% of the upper alluvial plain area, and 92.3% of lower alluvial plain area were classified correctly. Thus, clear distinctions were observed between the three regions, although a few parts of the pediplane area (3.6%) and lower alluvial plain (7.7%) overlapped with the upper alluvial plain.

2.4 Principal component analysis

Principal component analysis (PCA) was applied to the three respective regions of the basin to understand the factors that control channel morphology. It illuminated essential information about the applicable factors (Mühl, 2014). Channel morphology variables such as the drainage area, channel width, maximum channel depth, reach slope, average depth, channel cross-section area, width-to-depth ratio, discharge, shear stress, stream power, mean sediment grain size, and sinuosity index were selected for PCA analysis. This method was used to determine the principal controlling variables of the system and understand how they differed between regions.

3 Results

3.1 Downstream channel morphology and flow trends

The valley channel configuration and channel pattern variables are important to understanding the downstream channel morphology (Kemp, 2010). Straight to meandering channel patterns are observed between the source point in Bara Panjania and Bankura Town, which is in the pediplane area (Figs. 1c, 3a, and 4). A meandering channel pattern is observed in the upper alluvium area from Bankura Town to Rautara near the Eklakshmi Bridge. The flood plain is characterized by an unconfined channel, medium-sand-bedded riverbed, meandering scars, and channel avulsion. In the lower alluvium area, the river stretch extends from Ekalakshmi bridge to Bondor (the mouth), where an anabranching channel is found below the Girijatala (near Arambag, Hooghly) and joins the system before the river mouth at Bondor. In the lower alluvial plain, higher flows generally overflow from the channel, where they spread to the flood plain and palaeo channel. The bed level elevations of these subsidiary or palaeo channels are several meters above the main channel bed. A meandering channel pattern is found throughout this area. Flow and morphological character trends were considered for all stations. The channel reach between Girijatala and Banda exhibits a bifurcating channel condition. Therefore, the bifurcating section was not observed during this portion of the study. An observation occurred after the channel reach joins with the river near Bandor.

3.1.1 Pediplane area with a confined channel

The Dwarkeswar River passes the pediplane area through a single channel with a low gradient (1º to 5º) (Fig. 4) between sources and goes to Bankura Town. Next, it passes through a straight channel with a deep, narrow gorge (Fig. 6). The 1.6 km-wide flood plain area is characterized by a thin layer of soil constrained by metamorphic Archean age bedrock and Chhotanagpur Genessic Complex rock from the Proterozoic age (GSI, 2002). The major part of the channel is sinuous in nature, although a few parts of the river such as those near Rangamati, Bankura (Reach 15) and Balia, Bankura (Reach 21) exhibit meandering channel patterns (Morisawa and Clayton, 1985). Extensive sheet, rill, and gully erosion are observed over the highly weathered granite gneiss surface (GSI, 2002). This is a major source of coarse sand that is transported to the riverbed. The proportions of silt and clay in the bank material increase as one travels downward. Coarse bank textures are associated with confined river reaches. The cross-sectional shapes within the pediplane area vary from trapezoidal to rectangular (Fig. 6). The width/depth (W/D) ratio remains below 5.4 in reaches 1 through 3. The W/D ratio increases downward to 172.27 at the end of the pediplane area (Reach 28, Fig. 6). The average W/D ratio in this zone is 58.11 (Table 2). The bankfull width (W_{bf}), bankfull flow area (A_{bf}), bankfull mean depth (D_{bf}), and bankfull discharge (Q_{bf}) increase significantly as one travels downward (Fig. 7). The sinuosity index does not exhibit substantial trends. This suggests that the channel morphology slowly becomes dominated by hydrology instead of topography as one travels downstream. Fig. 7 shows that the bankfull width exhibits positive trends with a correlation value of 0.96, and that 91.24% of variability is explained. A strong positive relationship is noted between the bankfull width and the distance from source. The bankfull channel area also increases with

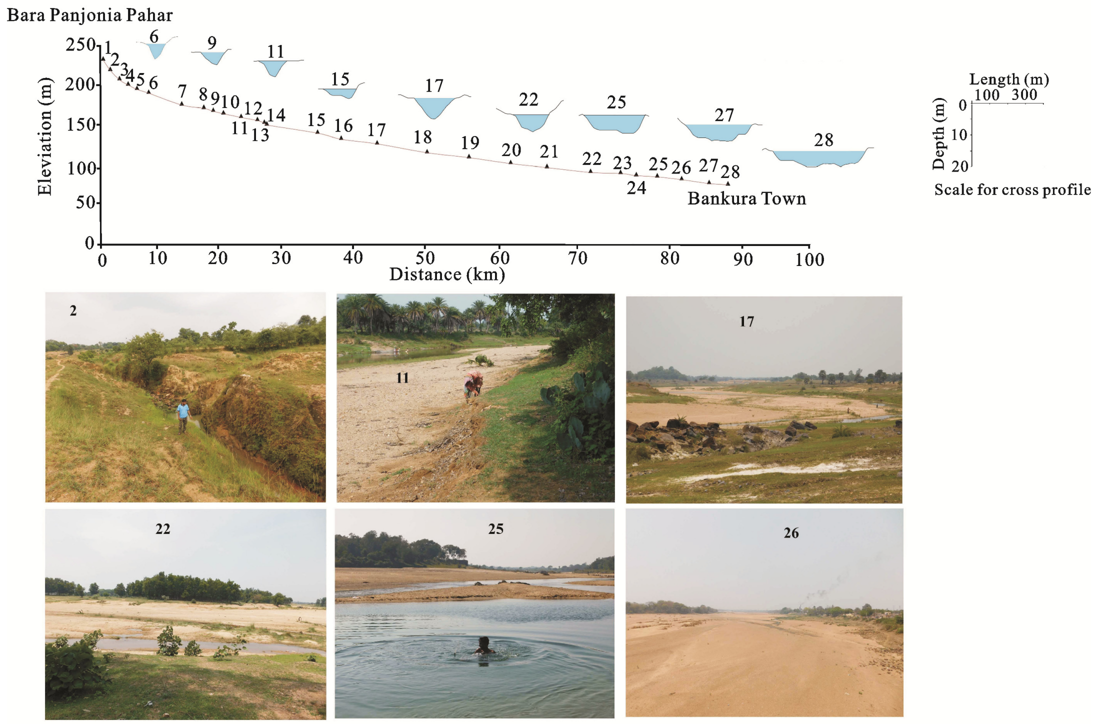


Fig. 6 Graphical representation of the channel cross-sections and images of the local environment in the pediplane area at various positions along the Dwarkeswar River, India. The numbers are the monitoring stations of the river reach in Fig. 1

the increasing distance from source in the pediplane region. The correlation value is 0.97, which indicates that 94.11% of channel area variability is explained by the distance from source. The bankfull discharge of the river also increases significantly with the increasing distance from source. The observed correlation value of 0.953 explains 90.90% of the variance. The width-to- depth ratio of this river increases in the downstream direction, although the growth rate is lower than that observed with other channel properties, as noted above (Fig. 7).

PCA allows one to extract the principal components based on a threshold of 1 eigenvalue. This relationship explains 85.11% of the variance in the third PCA (Table 3). In this analysis, we find that all of the variables are positively correlated in this system, except the minimum elevation, slope, and *W*/*D* ratio (Table 3). Table 3 also indicates that the minimum elevation, slope, and D50 sediments are strongly negatively correlated within this system. In contrast, the bankfull width, maximum depth, mean depth, flow area, and discharge influence the system in a substantially positive manner.

The correlation matrix indicates that the bankfull channel capacity increases with the drainage area, width, maximum depth, average depth, channel area, and *W*/*D* ratio (Table 5). The minimum elevation, slope, and average sediment size decrease significantly as the flow increases. As one moves downstream, the bankfull width, channel area, *W*/*D* ratio, and discharge also exhibit positive variation (Figs. 6 and 7). Thus, the pediplane area of the basin follows normal hydraulic equations (Fig. 7).

3.1.2 Upper alluvial plain with a wide-sand-bedded channel

Approximately 88 to 89 km from the source, the river enters an extensive flat, alluvial plain (Figs. 3a, 3b, and 4). Geologically, this region belongs to the unclassified Quaternary period. It tends to be highly permeable and includes sediment deposits dominated by sand, silt, and clay. Downstream of this point, the average channel gradient declines to 0.9 m per 1000 m and the terraces gradually merge into the floodplain. Some bedrock outcrops are present along the main course of the river near Mataranga (Reach 29). The long profile of this river is convex within this particular section (Fig. 3b). Flood features are pronounced in this less-confined zone. Examples include channel avulsion from areas near Pratappur (Reach 30) to Majdiha (Reach 33), the Loharara

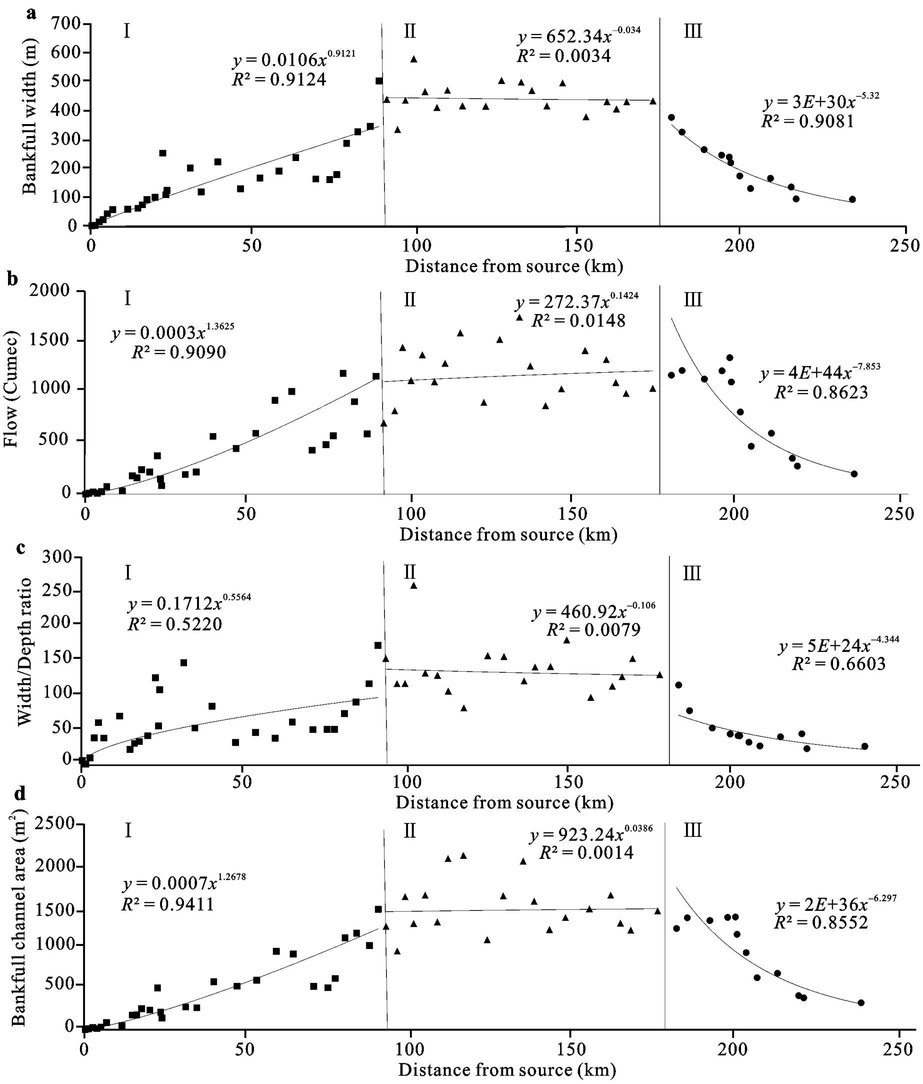


Fig. 7 Downstream variation of the Dwarkeswar River bankfull width (a), discharge (b), width/depht ratio (c) and channel area (d) in the pediplane (I), upper alluvial (Ⅱ) and lower alluvial areas (III) of the western part of West Bengal, India

Table 3 Responses of variables in principal component analysis

Variables	Pediplane area components			Upper alluvial plain components				Lower alluvial plain components		
	1	2	3	1	2	3	4	1	2	3
Drainage area	**0.93**	–0.08	–0.05	–0.20	**–0.89**	0.05	0.31	**–0.88**	–0.09	–0.28
Minimum elevation	**–0.97**	0.10	–0.01	0.08	**0.89**	–0.12	–0.35	**0.92**	–0.26	0.02
Bankfull width	**0.90**	–0.28	–0.08	–0.06	0.57	**0.70**	0.42	**0.97**	–0.16	–0.12
Bankfull max depth	**0.85**	0.45	0.11	**0.68**	0.35	0.50	–0.02	0.22	**0.90**	0.27
Bankfull mean depth	**0.75**	0.65	–0.07	**0.81**	–0.34	0.05	–0.44	0.14	**0.96**	–0.16
Width/depth ratio	0.54	**–0.65**	0.08	–0.43	**0.60**	0.43	0.50	**0.83**	–0.53	–0.13
Bankfull flow area	**0.95**	–0.06	–0.08	**0.73**	0.12	0.63	–0.07	**0.93**	0.29	–0.09
Slope	**–0.85**	0.12	–0.01	0.08	0.57	**–0.62**	0.49	**0.85**	–0.51	0.01
Flow	**0.94**	0.07	0.03	**0.95**	–0.03	0.21	0.15	**0.94**	0.26	–0.09
Shear stress	0.01	**0.85**	0.26	**0.77**	0.13	–0.45	0.38	**0.98**	0.13	0.01
Stream power	–0.10	**0.88**	–0.09	**0.76**	0.11	–0.57	0.25	**0.97**	0.12	–0.02
D50	**–0.78**	–0.12	–0.25	–0.21	**0.61**	–0.18	–0.31	–0.31	–0.31	**0.38**
SI	–0.14	–0.17	**0.95**	–0.33	–0.49	–0.05	0.13	0.24	–0.04	**0.90**

Note: Bold values are indicates the dominant role in different PCA

Table 4 Principal component analysis with four components: eigenvalues and the percentage of variance explained

Region	Component	Initial eigenvalues		
		Total	Proportion of variance (%)	Cumulative (%)
Pediplane area	1	7.34	56.46	56.46
	2	2.64	20.29	76.76
	3	1.09	8.35	85.11
Upper alluvial plain	1	4.11	31.59	31.59
	2	3.35	25.79	57.38
	3	2.36	18.14	75.52
	4	1.70	13.10	88.62
Lower alluvial plain	1	7.83	60.26	60.26
	2	2.65	20.42	80.67
	3	1.17	9.02	89.70

Table 5 Correlation matrix for morphological parameters of pediplane, upper alluvial plain, and lower alluvial plain of the Dwarkeswar River in the western of West Bangal, India

Region	Pearson correlation	Drainage area	Minimum elevation	Bankfull width	Bankfull max depth	Bankfull mean depth	*W*/*D* ratio	Bankfull flow area	Slope	Flow	Shear stress	Stream power	D50	*SI*
Pediplane Area	Drainage area	1.000												
	Minimum elevation	–0.925**	1.000											
	Bankfull width	0.830**	–0.863**	1.000										
	Bankfull max depth	0.749**	–0.774**	0.614**	1.000									
	Bankfull mean depth	0.626**	–0.673**	0.485**	0.909**	1.000								
	W/*D* ratio	0.473*	–0.573**	0.787**	0.162	–0.036	1.000							
	Bankfull flow area	0.886**	–0.881**	0.941**	0.770**	0.681**	0.558**	1.000						
	Slope	–0.745**	0.880**	–0.724**	–0.673**	–0.597**	–0.433*	–0.744**	1.000					
	Flow	0.862**	–0.851**	0.864**	0.835**	0.726**	0.447*	0.967**	–0.722**	1.000				
	Shear stress	–0.128	0.071	–0.191	0.380*	0.425*	–0.438*	–0.056	0.039	0.078	1.000			
	Stream power	–0.157	0.202	–0.234	0.287	0.462*	–0.449*	–0.111	0.348	–0.033	0.668**	1.000		
	D50	–0.719**	0.808**	–0.542**	–0.694**	–0.635**	–0.321	–0.602**	0.676**	–0.639**	–0.094	0.010	1.000	
	SI	–0.154	0.131	–0.135	–0.077	–0.250	0.093	–0.168	0.133	–0.088	0.056	–0.182	–0.031	1.000
Upper Alluvial Plain	Drainage area	1.000												
	Minimum elevation	–0.976**	1.000											
	Bankfull width	–0.181	0.140	1.000										
	Bankfull max depth	–0.094	–0.005	0.259	1.000									
	Bankfull mean depth	0.056	–0.133	–0.310	0.535*	1.000								
	W/*D* ratio	–0.200	0.203	0.874**	–0.071	–0.702**	1.000							
	Bankfull flow area	–0.085	–0.015	0.521*	0.726**	0.643**	0.057	1.000						
	Slope	–0.481*	0.479*	–0.117	–0.210	–0.378	0.158	–0.445	1.000					
	Flow	0.005	–0.104	0.231	0.715**	0.716**	–0.192	0.838**	–0.190	1.000				
	Shear stress	–0.299	0.237	–0.262	0.262	0.264	–0.301	0.025	0.699**	0.413	1.000			
	Stream power	–0.293	0.244	–0.363	0.254	0.335	–0.398	0.003	0.676**	0.432	0.971**	1.000		
	D50	–0.666**	0.716**	–0.198	–0.136	–0.194	–0.014	–0.352	0.474*	–0.454	0.137	0.168	1.000	
	SI	0.434	–0.388	–0.169	–0.140	–0.121	–0.077	–0.240	–0.200	–0.188	–0.235	–0.235	–0.228	1.000

Continued Table

Region	Pearson correlation	Drainage area	Minimum elevation	Bankfull width	Bankfull max depth	Bankfull mean depth	*W*/*D* ratio	Bankfull flow area	Slope	Flow	Shear stress	Stream power	D50	*SI*
Lower Alluvial Plain	Drainage area	1.000												
	Minimum elevation	–0.828**	1.000											
	Bankfull width	–0.769**	0.922**	1.000										
	Bankfull max depth	–0.421	0.011	0.033	1.000									
	Bankfull mean depth	–0.131	–0.134	0.021	0.830**	1.000								
	W/*D* ratio	–0.644*	0.896**	0.915**	–0.321	–0.362	1.000							
	Bankfull flow area	–0.757**	0.767**	0.892**	0.416	0.451	0.637*	1.000						
	Slope	–0.721**	0.887**	0.886**	–0.268	–0.384	0.974**	0.613*	1.000					
	Flow	–0.764**	0.767**	0.897**	0.383	0.425	0.655*	0.994**	0.645*	1.000				
	Shear stress	–0.870**	0.845**	0.923**	0.334	0.272	0.739**	0.948**	0.770**	0.964**	1.000			
	Stream power	–0.843**	0.815**	0.911**	0.298	0.268	0.735**	0.935**	0.771**	0.962**	0.993**	1.000		
	D50	0.224	–0.238	–0.220	–0.215	–0.294	–0.137	–0.301	–0.144	–0.319	–0.309	–0.324	1.000	
	SI	–0.372	0.234	0.118	0.201	–0.151	0.099	0.124	0.225	0.140	0.229	0.215	0.050	1.000

Notes: ** and *, indicates level of significance are 0.01 and 0.05 respectively

area (Reach 35), a meander scar and scroll near Srirampur (Reach 33), the Paikpara (Reach 36) area, the Joykrishnapur (Reach 37) area, etc. Floodway activity occurs along these channels during large flood flows. In addition, excessive bank erosion and channel shifting are common in this zone. The floodplain width varies from 900 m to 7 km, but averages 2.8 km within this zone. Throughout the floodplain, the muddy channel banks are partially cemented with mixed sand and silty point bars in bench deposits within the channel. In contrast, overbank deposits are characterized by fine sediment. Some reaches contain insignificant large woody debris from fallen trees that become visible after the monsoon season. The channel migration rate has not been measured, but the entire reach of this zone (which dates from the 1920s) exhibits significant changes in channel width, shape, and river bend positions. The river is not a single-threaded channel during low flow periods. Rather, it becomes an irregular braided-to-anastomosing channel with sand bars (Figs. 7 and 8). The W_{bf}, D_{bf}, A_{bf}, W/D ratio, Q_{bf}, bed shear stress, and stream power do not exhibit significant changes. Rather, they remain constant or monotonous in nature (Fig. 7). The downstream variation in the bankfull channel width, W/D ratio, and discharge are shown in Fig. 7 and are constant in nature. There is poor correlation (r = 0.0583) between the bankfull width and distance from source in this location. The increasing distance from source are insufficient to explain the bankfull width variation in the upper alluvial plain of this river, as the coefficient of variance is 0.0034. The bankfull channel area also exhibits linear trends (r = 0.037) with respect to the increasing distance from source. The W/D ratio of this river does not exhibit significant trends in the upper alluvial plain (r = 0.089), as it can explain only 0.79% of variation. Similarly, the bankfull discharge exhibits a linear trend in this area (r = 0.122) explaining only 1.48% of variability (Figs. 7 and 8). Intensive sand mining over the past 25 yr has increased the channel depth and decreased the overbank flow in this area.

Four components were extracted from the PCA of the upper alluvial plane. These components explained 88.62% of the total variance in the fourth PCA (Table 4). This analysis also indicates that the minimum elevation, bankfull width, maximum depth, mean depth, channel area, channel flow, shear stress, stream power, and W/D ratio are positively correlated within this system, but that the drainage area and slope are not (Table 3). Correlation analysis (Table 5) shows that the flow in this area is substantially related to the bankfull maximum depth, average depth, and flow area. The channel capacity and bankfull flow vary little, as indicated by Table 5 and Figs. 7 and 8.

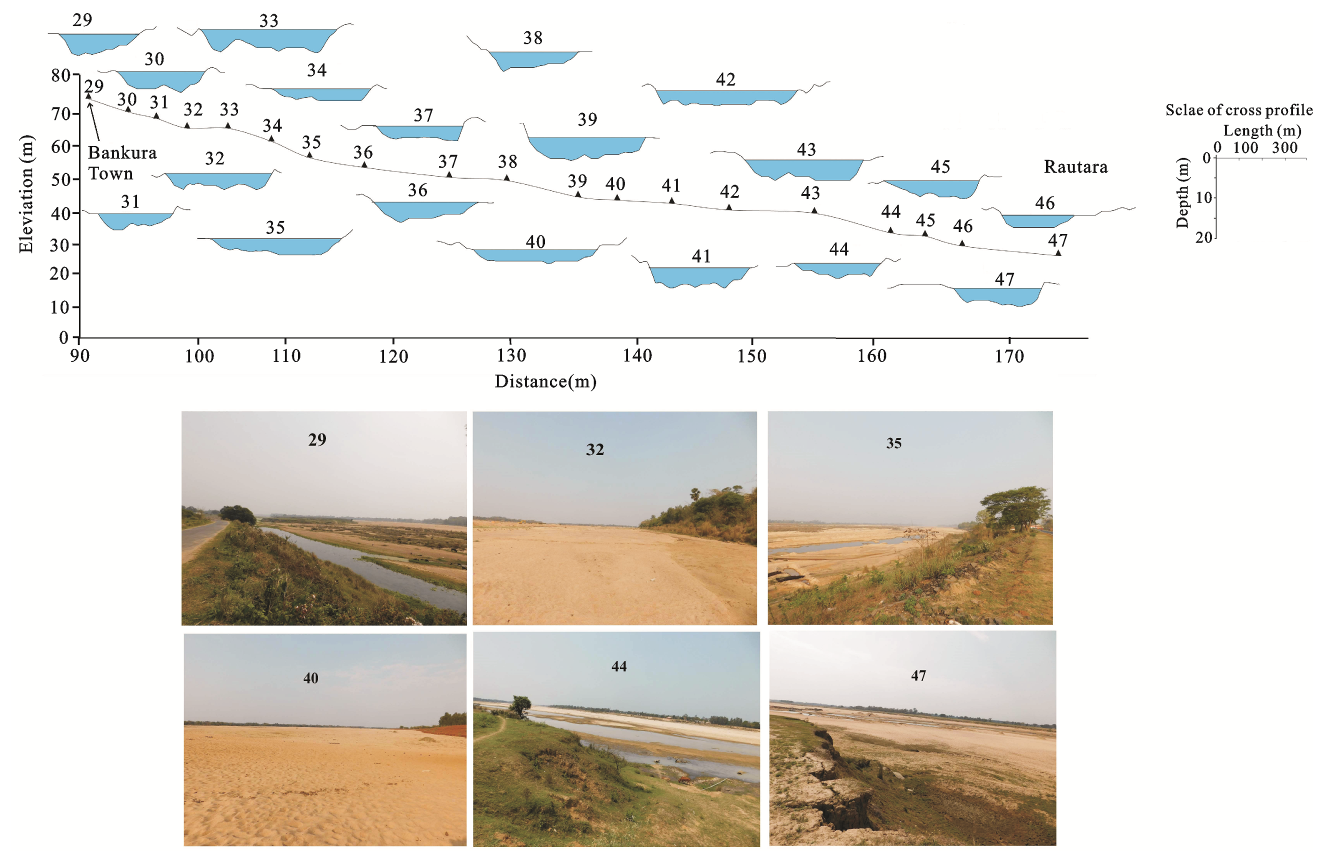


Fig. 8 Graphical representation of channel cross-sections and pictures of the local environment in the upper alluvium area along the flow direction of the Dwarkeswar River, India. The numbers are themonitoring stations of the river reach in Fig. 1

3.1.3 Decreasing channel capacity in the lower alluvial plain

The lower alluvial plain ranges from Rautara, (Burdwan District, Reach 48) to the mouth of the river near Bandor (Hooghly District, Reach 58). The river flows over Holocene deposits, including Chinsura formations characterized by sandy silt and dark grey clay. The Kana Dwarkeswar palaeo channel is located upstream of Arambag Town (Reach 51). It is thought to have been one of the main distributary channels in the recent past but is active only during peak monsoon floods, as its bed is approximately 9 m above the current channel.

Channel pattern changes can be found near Girijatala, below Arambag town (Hooghly District) in this lower recent alluvium zone. Here, a sinuous or meandering river becomes an anabranching channel that continues for 12.16 km, after which the branches recombine near Paschim Thakurani Chak in Hooghly District. After this, the river becomes straight (SI = 1.1). Of the bifurcated branches, the left was more active than the right during the 1970s (Topographical sheets by SOI) but with the passage of time and associated sedimentation on the left branch, the right branch channel has received more flow. This has led to degradation of the left channel, but sedimentation rates are insufficient to infill this channel. Presently, the left side of the channel is active only during peak flow. With regard to this, Makaske (2001) stated that a stable anabranching channel pattern may appear from an infrequent channel avulsion and with limited sedimentation to yield slow abandonment of old channels. On this portion of the Dwarkeswar River, anabranching appears to have produced a stable channel pattern, as it has been constant for the past two hundred years (Rennel, 1779; SOI, 1929; 1975) and is assumed to be undergoing similar channel abandonment processes. In this study, both anabranching channels are associated with highly elevated embankments. The bankfull width decreases sharply as the distance from source increases in the lower alluvial plain. The correlation coefficient between the distance from source and bankfull width is –0.953 and explains 90.81% of variation (Fig. 7). The bankfull channel area also exhibits a strong negative relationship with the increasing distance from source (r = –0.925) that explains 85.52% of variability. Similarly, the W/D ratio exhibits a negative correlation with the distance from source (r = –0.813) that explains 66.03% of variation. The bankfull discharge also indicates a decreasing downstream trend (r = –0.929) with respect to the increasing distance from source that explains 86.23% of system variation (Fig. 7).

In addition to these anabranching channels, sharp and significant decreases in the W_{bf}, A_{bf}, Q_{bf}, and W/D ratio may have contributed to frequent local floods. Embankment breaching (known locally as *Bali Hana*) is a well-known event for people who reside in these lower reaches. Several reports from the Irrigation and Waterways Directorate Govt. of West Bengal, (2017, 2016, 2013) have stated that improper drainage conditions and sluggish flow over this region are is the main reasons for frequent floods in the lower part of the river. Indications of tidal activity are also observed up to 10.32 km upstream from the river mouth. This can worsen the situation via flood tides that occur via development of a reverse hydraulic gradient and prevent the channel from discharging into adjacent waters (Bandyopadhyay et al., 2014). Continuous concretization and the increasing height of the embankment over the immediate channel bank have recently increased the channel infill rate and bed elevation.

Three principal components were extracted for the lower alluvial part of the basin. 89.70% of the variance is explained in the third PCA (Table 4). The PCA also shows that all the variables act together to control the system (Table 3). It is particularly interesting that the drainage area affects the system negatively, while the minimum elevation and slope are the dominant, positive controlling variables for the first principal component. The correlation matrix shows that the channel capacity and channel flow are negatively correlated to the drainage area and positively correlated to the minimum elevation and slope in a substantial manner (Table 5). This indicates that the channel area and flow capacity decrease as the drainage area increases downstream (Table 5 and Figs. 7 and 9).

3.2 Downstream flow changes

Downstream changes in the Q_{bf} increase up to the upper alluvial region zone but start to decrease from 1877.55 m^3/s to 357.08 m^3/s in the lower alluvial flat plain (Fig. 7). The bankfull flow frequency has been analyzed using gauge height data. The results indicate that floods occur when the flow level crosses the bankfull height. The bankfull flow frequency varies downstream. It is 4.6 yr near Arambag (Reach 52) but 2.7 yr near Sheikpur (reach 58, before the start of the anabranching point) (Fig. 10). Near the river mouth

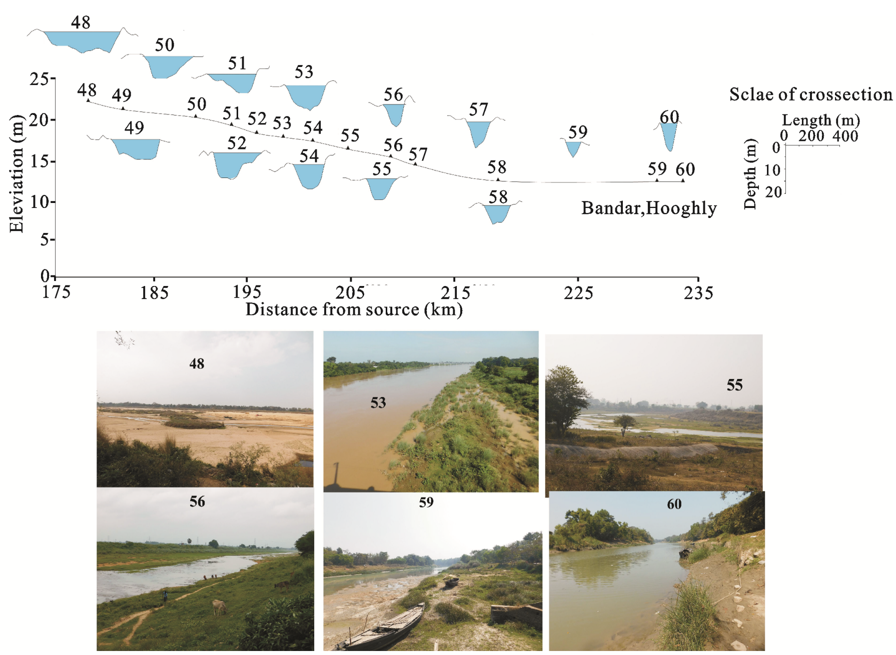


Fig. 9 Graphical representation of the channel cross-sections and pictures of the local environment in the lower alluvium area along the flow direction of the Dwarkeswar River, India. The numbers are themonitoring stations of the river reach in Fig. 1

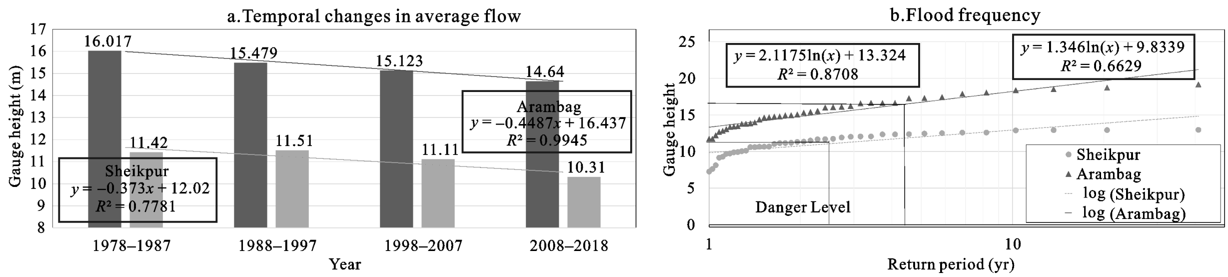


Fig. 10 Temporal changes in flow (a) and flood frequency analysis (b) based on measurements made at Arambag and Sheikpur stations of Dwarkeswar River, India

(Bandar, Reach 60), the bankfull flow frequency decreases to 1.4 to 1.7 yr. This last value was determined via discussions with local older people near the Bandar mouth of the river. Construction of several small dams after the 1990s in the upper catchment (pediplane area) of the river and excessive river bed sand mining have led to decreases in the river channel flow height (Fig. 10). The mean bankfull velocity decreases downstream. The average velocity in the upstream part of the basin is 2.23 m/s, but this decreases to 1.59 m/s in the middle. However, the average velocity increases to 1.61 m/s in the lower part of the river. This may be due to the decreasing *W/D* ratio, bankfull channel area, and channel adjustment. Since it is an elongated river, flash flows are inherent to the Dwarkeswar River. This has been confirmed via stage flow data and conversations with local people. Thus, the decreasing channel capacity, increasing flow velocity, and inability to discharge excess flow have increased the frequencies of embankment breaching (known locally as *Bali Hana*) and flooding. The latter is a frequent, devastating event for people who reside in the lower part of the river.

Manning's roughness coefficient (n) decreases in the downstream direction. The average n value of 0.044 found in zone one increases to 0.039 in the middle and lower reaches. In the lower portion of the river, roughness values are affected primarily by the presence of tall grass along the riverbank and small grasses on the riverbed. In addition, the presence of several earthen barriers intended to store flow affects the n value. The specific stream power levels of the pediplane, upper alluvial, and lower alluvial portions of the river are 31.46 W/m^2, 17.72 W/m^2, and 18.73 W/m^2 respectively. This indicates downstream declines in the specific stream power. The mean channel depths increase continuously. For example, the average bankfull channel depths of the pediplane, upper alluvial, and lower alluvial portions of the river are 2.57 m, 3.27 m, and 4.58 m, respectively. This produces average bed shear stresses of 24.36 N/m^2, 16.97 N/m^2, and 16.91 N/m^2, respectively (Table 2).

4 Discussion

4.1 Channel morphology trends

Downstream channel morphology variation has been studied by several scholars and has became a tenet of modern fluvial geomorphology (Nanson and Young, 1981). Channel dimensions increase at various rates in the downward sections of rivers. However, the most striking downstream trend on the Dwarkeswar is the tendency of A_{bf}, W_{bf}, and Q_{bf} to decrease in the downstream direction (Table 5, Figs. 7 and 9) although the river travels from a semi-arid region (annual rainfall below 1300 mm) to sub-tropical area (annual rainfall of 1500 mm to 2000 mm). Between its source and mouth, the river flows over various geologic and topographic regions that affect its channel dimensions substantially. However, the river becomes more complex after crossing the middle section. The bankfull flow and flood flow frequencies increase and the bankfull channel dimensions decrease. The bankfull channel flow rate decreases as one moves downstream. This accelerates the transition to multiple channels, partly through attenuation effects. This causes large energy and water declines, but is presently being combated by increasing embankment heights. The consistent downstream bankfull frequency increase is a reflection of short duration, higher frequency floods in the lower reaches of the river. The bankfull channel width reaches its maximum of 689.48 m at cross-section no. 35 in the upper alluvial area and decreases to 68.45 m at the mouth at Reach 60. In addition, the bankfull flow area reaches its maximum of 2117.13 m^2 at cross-section no. 36 in the upper alluvial area but decreases to 279.14 m^2 near Reach 60 at the river mouth. Thus, width decreases that exceed a factor of 10 and channel decreases that exceed a factor of 7.5 are noted (Figs. 7 and 8). This clearly shows that the Dwarkeswar River diminishes as it moves downstream.

Such changes cannot be explained simply. Downstream channel morphology trends associated with perennial streams are also found in ephemeral streams (Kale and Gupta, 2001; Kemp, 2010). However, Park (1977) and Wolman and Gerson (1978) have argued that the associated rates of change are different from those associated with perennial streams. Several studies have shown downstream channel morphologies that decrease instead of increasing. For instance, Zimmerman et al. (1967) stated that channel dimensions in northern Vermont did not increase downwards until the basin area exceeded approximately 0.5 km^2 to 2.0 km^2. This was probably due to elimination of discharge effects via vegetation encroachment. However, our study area includes a much larger area than that considered by Zimmerman et al. (1967). Downstream decreases in channel dimensions were also reported by Kemp (2010), Tooth (2000), and Nanson and Young (1981), particularly for ephemeral streams from arid areas (Fig. 11). In semiarid environments, channel dimensions and flood volumes decrease downstream because of transmission losses (Dunkerley, 1992; 2008). In this study, the pediplane area of the river is in a semi-arid area, although it exhibits natural downstream channel dimension increases until Bankura Town (Fig. 7). After crossing Bankura Town, the riverbeds enlarge substantially and remain constant in the downward direction until the start of the lower alluvial plain. In contrast, decreasing channel dimensions are noted in the lower alluvial plain. Fig. 7 shows that there are marked differences in channel parameter trends with respect to the drainage basin. The relationships between the bankfull channel width, bankfull area, *W*/*D* ratio, and bankfull discharge and the increasing drainage basin area are large and positive in the pediplane area, constant in the middle reaches, and significantly negative in the lower section (Fig. 7). PCA analysis shows that there are marked changes in principal controlling factors (Table 3). The PCA table (Table 3) indicates that the drainage area, minimum elevation, and slope play substantial, positive roles in the river system in the pediplane area but become negative in the lower alluvial area (Fig. 7). Nanson and Young (1981) found that the channel dimension decreases as the flood plain width and bankfull flow increase when cohesive bank materials are present. This coincides with our observations of the Dwarkeswar River although the latter has a different fluvial regime and hydrologic environment. Wohle (2004) states that downstream hydraulic geometric relationships do not develop properly if the ratio of sediment size to stream power falls below 10 000 kg/s^3.

4.2 Causes of channel decreases

Decreases in channel capacity may be caused by decreased precipitation, up-basin storage, diversion, clogging of off-takes, or discharge changes. However, there is no reliable evidence of decreasing monsoonal precipitation between 1901 and 2003 (Guhathakurta and Rajeevan, 2006; Guhathakurta et al., 2011). Therefore, these decreases cannot simply be explained via anthropogenic activities.

4.2.1 Palaeo channel degradation

Bandyopadhyay et al. (2014) stated that river degeneration in abandoned deltas and lower alluvial areas occurs due to channel course changes with time. This seems to be valid in the case of the Dwarkeswar River, where several palaeo channels can be identified in the lower part of the basin. The same area is associated with decreasing channel dimensions. Previously, these palaeo channels were the distributary channels of the river. However, deforestation-driven sedimentation in the upper part of the river basin during the 18th century and other anthropogenic factors detached these distributary

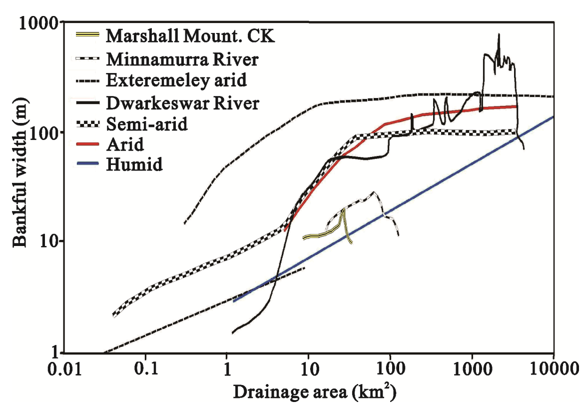


Fig. 11 Relationship between the bankfull channel width and the drainage area (Modified after Tooth, 2000; Knighton and Nanson, 1997; Wolman and Gerson, 1978 and data compiled from several sources, including Leopold and Miller, 1956; Nanson and Young, 1981; Kemp, 2010 and our study area

rivers from the main course of the river. In addition, flood flow situations spread river water to the surrounding flood plain regions. As a result, the main course of the river suffers from lack of water to readjust its cross-section and re-form channels (Fig. 4).

4.2.2 Accelerated infiltration rates

Rudra (2011) has emphasized that lowering of bankfull discharge may occur due to the presence of large-scale sand beds in the east-flowing rivers of West Bengal. In this study, we have also observed a vast sandy riverbed in the upper alluvial area of the Dwarkeswar River (Fig. 8). Large sand beds facilitate accelerated water infiltration rates, which can reduce the quantity of river water available. Kemp (2010) and (Tooth, 2000) have also shown reductions in the bankfull channel area due to accelerated infiltration of large river sand beds. In this study, a large sand bed was observed in the middle course of the river. River water started to infiltrate underground from the middle course of the river bed. In the lower course of the river, the river discharge decreased progressively relative to the previous section of the river reach.

4.2.3 Deforestation and sedimentation within a channel

Deforestation is a significant phenomenon in this region. Several historical accounts have stated that this upper part of the basin area was previously associated with thick forest but that massive deforestation occurred during British rule (Hunter, 1877, 1883; Duke, 1939; Biswas, 1976; Sinha, 2016; Siddique, 1996). In addition, District Census reports from Birbhum (1961) and Siddique (1996) indicate that the Damodar and Dwarkeswar Rivers were navigable using country boats at least until the mid-eighteenth century. Thus, massive deforestation may have accelerated the sediment load, leading to sediment deposition within the channel and channel area decreases (ASCE Task Committee, 1998) (Figs. 12a and 12b). Presently, these channels in the lower part of the river behave like as though they have experienced aggradation.

4.2.4 Other factors

Several other scholars have emphasized that anthropogenic activities like embankment changes, dam construction, transport network formation, land-use changes, deforestation, mining, extension of agriculture, water storage, and channel diversion may have combined with tidal silting and decreased precipitation to contribute to diminishment of the downstream channel (Rudra, 2009; Mukhopadhyay, 2010; Pal and Let, 2013; Bandyopadhyay et al., 2014; Ghosh and Guchhait, 2014). The topographical maps published by the Survey of India during the 1920s to 1930s indicate that overall channel plan-forms were similar to the present. Previous studies indicate that most of the relevant factors are anthropogenic (Mukhopadhyay, 2010; Pal and Let, 2013; Ghosh and Guchhait, 2014). However, such activities became prevalent only after 1950 (Bandyopadhyay et al., 2014). This leads one to question the dominance of anthropogenic activity. However, the rapid rate of structural development in this region starting in the 1990s, including new embankment construction, increased embankment heights, small and medium dam construction (Bandyopadhyay et al., 2014), groyne construction (Malik and Pal, 2019a; 2019b), and other anthropogenic activities have contributed to decreased river channel capacities. In addition, these activities have become

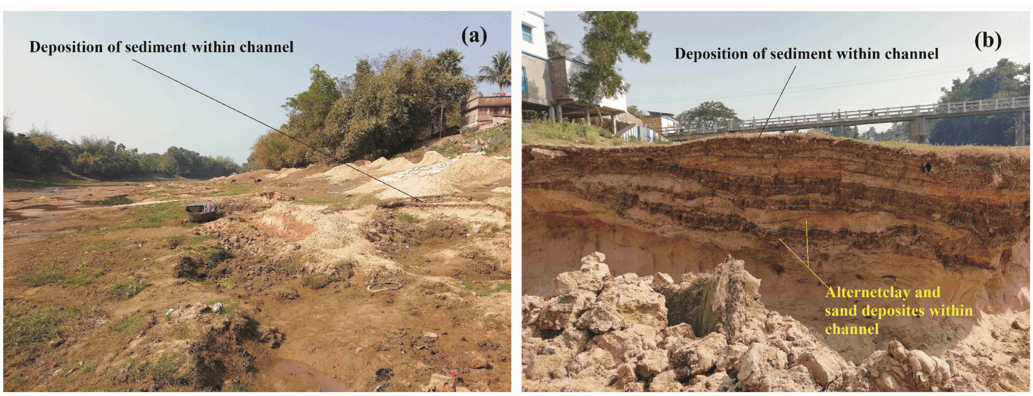


Fig. 12 Images of deposition within channels along the lower alluvial area (Below Girijatala, Arambag, Hooghly), of Dwarkeswar River, India

important barriers to enhancing the required channel capacity, particularly in the lower alluvial part of the river. Furthermore, the transition from single to multiple channels has contributed to decreased channel capacities (Bandy-Opadhyay et al., 2014). In this study, we have also observed a transition from single to multiple channels from the Girijatala (Reach 58).

A tendency towards increases in bankfull flow is noted until the middle reaches of the river, but decreases in bankfull channel dimensions in the downstream direction are similar to those noted in other rivers in the western part of Bengal Basin (Chakrabarti, 1985; National Disaster Management Authority and Government of India, 2008; Das et al., 2013; DoIW- GoWB, 2014; 2015; 2016; 2018; Ghosh and Guchhait, 2016; Irrigation and Waterways Department, 2016). This commonly reflects the flood-prone character of the lower part of the Bengal river system. Thus, our purpose in describing downstream degradation of Dwarkeswar River channel dimensions is not to discredit the river geometry and hydrology concepts developed by Leopold and Miller (1956), but rather to emphasize their limitations. This is supported by studies performed by Nanson and Young (1981), Kemp (2010), and Tooth (2000).

5 Conclusions

The Dwarkeswar River flows from a semi-arid, undulating pediplane to sub-tropical, humid, low-gradient alluvial plains. The bankfull channel width, depth, channel capacity, *W/D* ratio, flow velocity, and discharge increase in the pediplane region but vary little in the middle. However, the channel shrinks in the lower part of the river course as the drainage basin size increases. Sediment deposition within the channel, palaeo channel degradation, accelerated infiltration rates, deforestation in the upper pediplane area, and anthropogenic factors are the major causes of channel degradation in the lower section of the river. Because of this, floods have become an inevitable part of life for the people residing in the area. Floodplain zonation and restriction of human encroachment based on flood intensity may aid in sustainable development. In this study, we demonstrated the decreasing channel morphology of the Dwarkeswar River and probable reasons for the changes mentioned. The factors responsible for such channel morphology changes can be studied further.

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