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ScienceDirect
Geomorphology 86 (2007) 144 – 175
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Sediment characteristics and transportation dynamics of the Ganga River

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Received 24 January 2006; received in revised form 25 August 2006; accepted 25 August 2006
Available online 17 October 2006

Abstract

Understanding of river systems that have experienced various forcing mechanisms such as climate, tectonics, sea level fluctuations and their linkages is a major concern for fluvial scientists. The 2525-km-long Ganga River derives its fluvial flux from northern part of the Indian subcontinent and drops in the Ganga–Brahmaputra delta and the Bengal fan regions. This paper presents a study of the Ganga River sediments for their textural properties, grainsize characteristics, and transportation dynamics. A suite of recently deposited sediments (189 bedload samples and 27 suspended load samples) of the river and its tributaries was collected from 63 locations. Dry and wet sieve methods of grainsize analysis were performed and Folk and Ward's parameters were calculated. Transportation dynamics of the sediment load was assessed by means of channel hydrology, flow/sediment rating curves, bedform mechanics, grainsize images, and cumulative curves.

Textural properties of the bedload sediments of the Ganga River tributaries originating from the Himalaya orogenic belt, the northern Indian craton and the Ganga alluvial plain regions are characterised by the predominance of fine to very fine sand, medium to fine sand, and very fine sand to clay, respectively. Downstream textural variations in the bedload and suspended load sediments of the Ganga River are, therefore, complex and are strongly influenced by lateral sediment inputs by the tributaries and channel slope. At the base of the Himalaya, a very sharp gravel–sand transition is present in which median grainsize of bedload sediments decreases from over −0.16 Φ to 2.46 Φ within a distance of 35 km. Downstream decline in mean grainsize of bedload sediments in the upper Ganga River within the alluvial plain can be expressed by an exponential formula as: mean grainsize (in Φ) $=0.0024\times$Distance (in kilometres from the Himalayan front)$+1.29$. It is a result of selective transport phenomena rather than of abrasion, the condition attributed to channel competence with low gradient of 70 to 25 cm/km. Coarsening of the bedload sediments in the middle segment of the river develops due to the coarse bedload sediments (mean grainsize: 1.8–2.2 Φ) supply from the tributaries of the northern Indian craton region and increased unit stream power. The Ganga River sediments show a wide range of grainsize parameters [Bedload sediments: mean grainsize (1.5–3.8 Φ), standard deviation (0.3–0.7 Φ), skewness (−0.2–0.5), and kurtosis (0.8–2.4); suspended load sediments: mean grainsize (2.9–5.0 Φ), standard deviation (0.6–1.6 Φ), skewness (−0.6–0.4), and kurtosis (0.7–4.6)]. Mean grainsize of the bedload sediments is 2.6 Φ, which is 1.3 Φ units coarser than the suspended load sediments.

The cumulative grainsize curves of the bedload sediments show a distinct "break" in slope, representing nearly 80% of the bedload sediment transported as graded suspension. During the peak monsoon discharge, most of the bedload sediments are transported as the discontinuous, fine sandy, graded suspension by the unidirectional unsteady shooting flow at a high transport rate (about 8×10^6 tons/d). A model of sedimentation transportation at river channel is proposed. The Ganga River mobilises a total of 729×10^6 tons of sediments annually through a narrow zone within its river valley. Under the present hydrogeological conditions,

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0169-555X/$ - see front matter
doi:10.1016/j.geomorph.2006.08.011

the river sedimentation is climatically controlled and is predicted to produce a 2000-km-long, 2- to 40-km-wide and 25- to 50-m-thick ribbon-shaped, well-sorted symmetrically skewed fine sand body.

Keywords: Bedload sediments; Suspended load sediments; Sediment transportation; Grainsize; Monsoon climate; Ganga River

1. Introduction

Erosion, transportation, and deposition processes of terrigenous clastic sediments are essentially controlled by crustal deformation and climate. These clastic sediments are delivered to the oceans by rivers from the continents and represent the archives of the Earth's geological history by recording the effects of tectonics, climatic changes and eustasy. Sediments transported annually to the oceans are estimated at about $15–16 \times 10^9$ tons. The considerable morphodynamic energy provided by the continuing tectonic evolution of the Himalaya is expressed in high erosional potentials and very high rates of sediment production. Approximately half of the sediment discharge to the oceans, therefore, originates from the rivers of Southeast Asia. Rivers originating from the Himalaya contribute as much as 20% of the global sediment input (Milliman and Meade, 1983). The Ganga River is one of the most dynamic components of the Indian subcontinent and ranks among the world's major rivers. Along with the Brahmaputra, the Ganga River is also responsible for the creation of one of the largest deltas and the deep sea fans with one of the thickest sedimentary sequences in the world. It currently transports nearly 440×10^9 m^3 of water and 729×10^6 tons of sediment loads annually to the Bay of Bengal (Fig. 1). About 95% of the sediment load is transported during the monsoons and as much as 50% of the total annual water discharge moves nearly within a week's time. More than 70% of the sediment load of the river in the delta is silt, with an additional 10% sand (Coleman, 1969).

Studies of the Ganga River have focused on various aspects such as: (i) weathering, erosion and sediment transport (Abbas and Subramanian, 1984; Sinha and Friend, 1994; Goodbred, 2003; Vance et al., 2003; Wasson, 2003; Chauhan et al., 2004; Singh et al., 2005), (ii) fluvial geomorphology and sedimentology (Singh and Rastogi, 1973; Wells et al., 1983; Godbole, 1986a,b; Singh et al., 1990; Singh and Bhardwaj, 1991; Singh and Singh, 1992; Richards et al., 1993; Singh et al., 1998; Srivastava and Singh, 1999; Shukla et al., 1999, 2001; Srivastava et al., 2003; Barnard et al., 2004; Shukla and Singh, 2004), (iii) hydrology (Basu, 1967a,b; Das Gupta, 1975; Pandey, 1980; Das Gupta, 1984; Nandargi and Dhar, 1998), (iv) sediment mineralogy (Jha et al., 1993; Singh et al., 1993; Chakrapani et al., 1995; Datta and Subramanian, 1997; Heroy et al., 2003; Tiwari et al., 2004), (v) geochemistry (Ramesh and Sarin, 1992; Subramanian, 1993; Moore, 1997; Sarkar et al., 2003; Chakrapani, 2005), (vi) the Ganga–Brahmaputra delta characteristics and its evolution (Umitsu, 1993; Goodbred and Kuehl, 2000; Heroy et al., 2003; Singh and Swamy, 2006), (vii) environmental studies (Somayajulu et al., 2002; Singh et al., 2002, 2003), (viii) late Quaternary climatic studies (Kale et al., 2003; Singh, 2004), etc. An overview of the Ganga River is provided by Singh (in press).

Grainsize characteristics and transportation dynamics of river sediments have attracted the attention of numerous geologists and engineers over the years (Allen, 1965; Coleman, 1969; Whetten et al., 1969; Knighton, 1980; Brierley and Hickin, 1985; Gary and Hickin, 1985; Bridge et al., 1986; Garde and Raju, 2000; Surian, 2002). Little information is available on the grainsize characteristics and transportation dynamics of recent sediments of the Ganga River.

The Ganga River provides an opportunity to study its sediments for a better understanding of a climate-sensitive, continental-scale fluvial system and to interpret ongoing weathering and erosional processes of the Indian subcontinent. These sediments also act as a major transport medium for nutrients (such as nitrogen and phosphorus) and contaminants (such as heavy metals, pesticides, and herbicides). A knowledge of fluvial processes involved in the generation, transportation, and deposition of river sediments is clearly of fundamental importance in the Earth system science to enhance our understanding of the fate of chemicals under monsoon-controlled climatic condition. It will also help to increase our knowledge of various processes of a fine sandy fluvial system that will enable geomorphologists, hydrologists, fluvial geologists, and civil engineers to make credible long term plans for better use and management of the Ganga River for millions of people.

2. Regional setting

2.1. The Ganga River basin

The Ganga River basin (GRB) has an area of 1.086×10^6 km^2. It encompasses the Himalaya orogenic belt with deep valleys and glaciers in the north, plateau and hills of the northern Indian craton region in the south, and the Ganga alluvial plain in the middle and accounts for 21.6%, 55.4%, and 23.0% of the basin area, respectively. The basin supplies vast quantities of sediments from the erosion of the Himalaya orogenic belt and the northern Indian craton regions, slope erosion of the Himalayan foothills and sheet erosion of the Ganga alluvial plain. The drainage network of the Ganga River acts as a pathway for water and sediment discharges from the river basin to the Ganga–Brahmaputra delta and the Bay of Bengal regions (Fig. 1). At the mouth of the delta, the submarine canyon (Swatch of No Ground) plays an important role in allowing sediments to bypass into deeper waters of the Bay of Bengal and finally depositing in the deep sea fan. During the Last Glacial Maximum, the upland surfaces and incised valleys of the Ganga alluvial plain extended over the continental shelf and were connected with the Bay of Bengal via this canyon. The Bay of Bengal is one of the highest terrigenous input sites of the world.

2.2. Climate

The GRB has a humid subtropical climate characterised by four seasons: winter (January–March), summer (April–May), monsoon (June–September), and post-monsoon (October–December). January is the coldest month with temperatures below 10 °C. Low temperatures are often associated with rain showers in the western region of the basin. During the summer season, May is the hottest month in the greater part of the basin, except for the delta region. The Ganga River discharge shows strong seasonal variation to monsoon rainfall and discharges often described as monsoon, post-monsoon, winter and summer (Das Gupta, 1984).

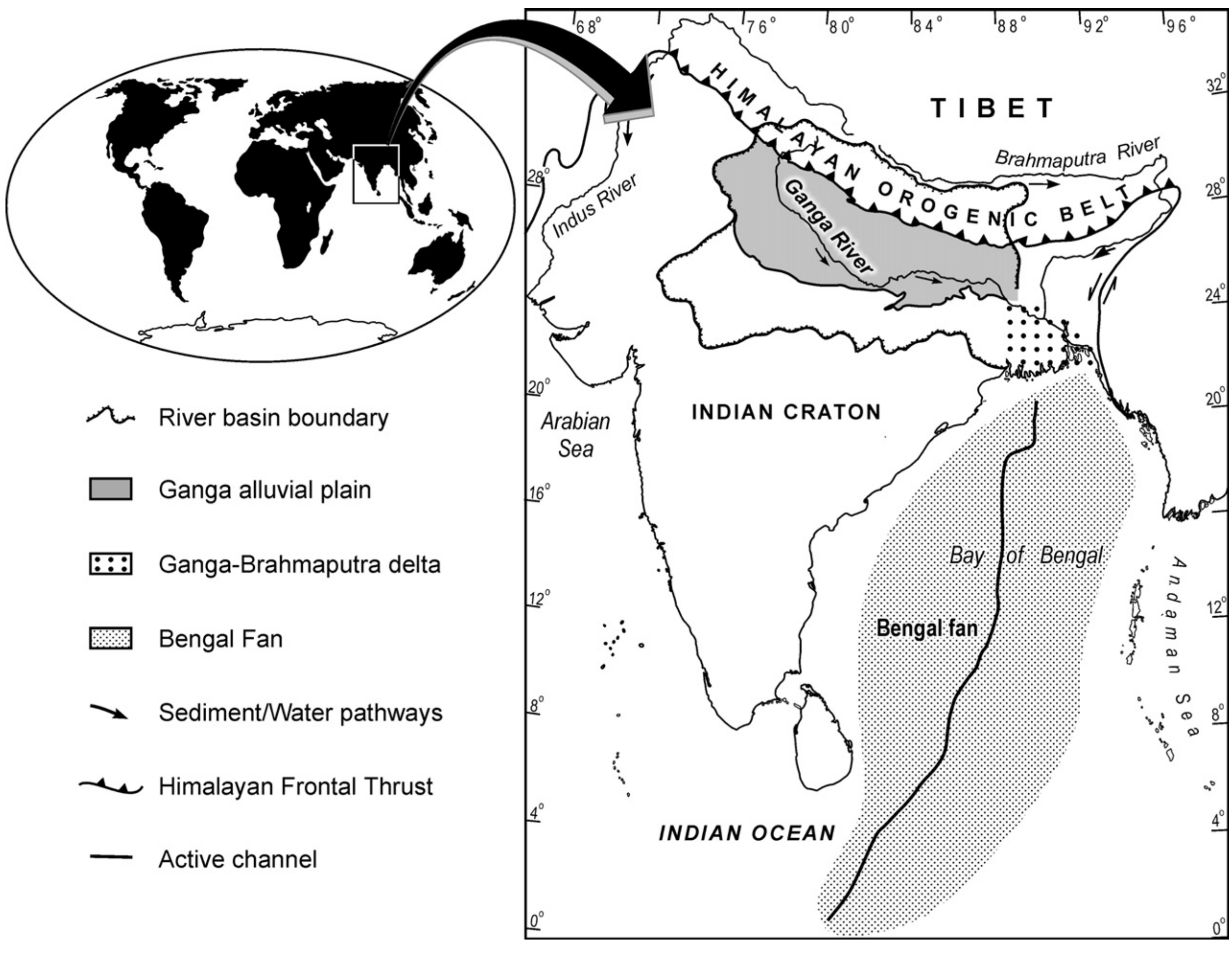

Fig. 1. The Ganga fluvial system is one of the most prominent geomorphic features of the Indian subcontinent and is responsible for creation of the Ganga–Brahmaputra delta and the Bengal deep sea fan. Quartz-rich terrigenous sediments (derived from the Himalaya orogenic belt, the Ganga alluvial plain and northern Indian craton regions) are being carried by the Ganga River through its valley.

The onset of monsoon normally occurs in early June at the mouth of the delta region. By the end of July, the monsoon establishes itself over the entire basin. Heavy rainfall occurs everywhere during July, August, and September. Usually 70–80% of the total annual rainfall occurs during this period. The wet season is much longer in the eastern part of the basin compared to the western part. This monsoon rainfall is also characterised by a declining trend, increasing with distance from the Bay of Bengal: Calcutta receives 1200 mm during the monsoon period, Patna 1050 mm, Allahabad 760 mm, and Delhi 560 mm. The average rainfall varies from 500 mm at the western end of the river basin to more than 1400 mm at the eastern end (Singh, 1997). Fig. 2A shows isohyets and spot heights in the GRB. The monsoon season comes to an end by the first week of September and begins to retreat gradually from the basin by the end of September. The intensity and duration of monsoon rains affects human life in the basin. For the greater part of the year, dry conditions prevail over the basin and a large amount of water is lost through evapotranspiration. The basin receives one million m^3 of water in each km^2 annually as rainfall. Nearly 30% of it is lost through evapotranspiration, 20% goes to ground water and, only 50% is available as surface flow in the basin (Das Gupta, 1984).

2.3. Geology

The GRB is closely linked with continent–continent collision of the Asian and Indian plates that has led to the development of the Himalaya orogenic belt. In front of the orogenic belt, the Ganga foreland basin has developed on the underthrusting flexed Indian plate. The Indian plate is still underthrusting the Asian plate and makes the basin tectonically active due to compressional forces, as shown in a schematic cross section in Fig. 2B. The geological boundaries correspond broadly with the geomorphic subdivisions of the GRB. Fig. 3 displays major lithologies of the GRB. Geologically, the Himalayan region is composed of four geological units separated by major thrust systems: Tethyan sedimentary series, the higher Himalayan crystalline series, the lesser Himalaya, and the outer Himalaya. The Tethyan sedimentary series is present largely on the southern edge of the Tibetan plateau and is composed of Palaeozoic–Mesozoic carbonates and clastic sediments. The higher Himalayan crystallines that contain up to 8000-m-high peaks in the Himalaya, consists of orthogneisses, paragneisses, migmatites, and highly metamorphosed sediments. The lesser Himalaya has break in a slope and more subdued topography compared to the higher Himalaya, and consists of metamorphosed and unmetamarphosed Precambrian sequences. The outer Himalayan belt consists of the recently uplifted Siwaliks of Miocene–Pleistocene detrital sediments, namely coarse sandstones, clays, and conglomerates. The northern Indian craton region of the basin consists of the Aravalli Range, the Bundelkhand Plateau, the Vindhyan Range, the Malwa Plateau, and the Chotanagpur Plateau, which are mainly composed of various rock types of mostly Archean and Proterozoic ages. The Ganga alluvial plain represents the alluvial filling of sediments derived from the Himalaya and the northern Indian craton regions during the late Pleistocene–Holocene. Detailed geology of the Ganga alluvial plain has been described elsewhere (Singh, 1987, 1996a).

The bedload sediments in the proximal part of the Ganga River are mainly composed of 81% quartz, 3% feldspar, 3% mica, 4% rock-fragments and 8% heavy minerals. In the heavy minerals, brown and blue varieties of tourmaline, colourless garnet, zircon and muscovite are the dominant species (Singh et al., 1993).

2.4. Drainage network

The drainage network of the Ganga River consists of a wide range of rivers that act as tributaries. These rivers are classified into three categories on the basis of their source area characteristics: (i) Himalayan-source rivers, (ii) Ganga alluvial plain-source rivers, and (iii) northern Indian craton-source rivers (Singh, 1996a, 2004). Rivers originating from the central Himalaya orogenic belt region are the main tributaries, which are perennial in nature, having L-shaped longitudinal profiles with high sediment discharge. Tributaries from the craton region are also perennial in nature with smooth longitudinal profiles. The Ganga alluvial plain tributaries originate from the interfluvial area of Himalayan rivers and are characterised by a very smooth longitudinal profile, moderate sediment supply, and a single sinuous course and little erosional capacity.

2.5. The Ganga River

The valley morphology of the 2525-km-long Ganga River reflects changes in hydraulic regime, sediment load, tectonic stability, river basin geology, and their interactions. On the basis of distinctive assemblages of valley morphology and channel characteristics, the (Ganga River valley) GRV has been divided into seven segments (Singh and Singh, 1992; Singh, 1996a,b, 2001). These are GRV-0: Gaumukh to

Haridwar; GRV-I: Haridwar to Garhmuktesar; GRV-II: Garhmuktesar to Allahabad; GRV-III: Allahabad to Buxar; GRV-IV: Buxar to Barh; GRV-V: Barh to Farraka; and GRV-VI: Farraka to the Bay of Bengal. Many of the geomorphic features of the Ganga River and its valley suggest strong neotectonic activity in the area (Singh, 2001). The GRV-0, GRV-I to V, and GRV-VI segments represent the Himalaya, the Ganga alluvial

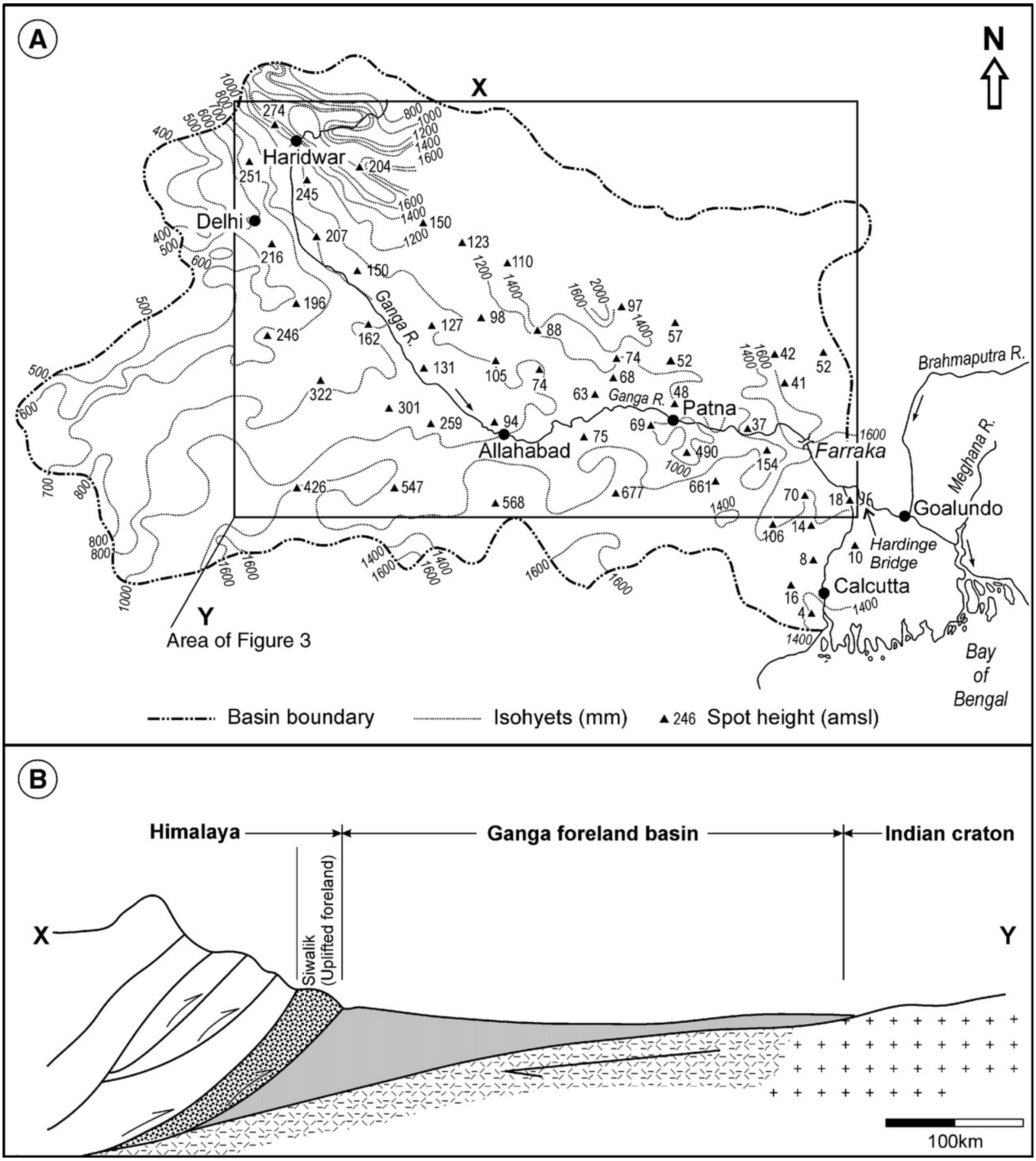

Fig. 2. The Ganga River basin showing (A) annual rainfall isohyets (generalised from NATMO, 1996) and (B) schematic cross section of the Ganga foreland basin (modified after Singh, 1996a).

plain, and the Ganga–Brahmaputra delta regions, respectively. The brief description of each segment follows:

The GRV-0: The Ganga River has its source at Gaumukh (30°36′ N; 79°04′ E) in the snout of the Gangotri Glacier under the name of Bhagirathi River in the higher Himalaya at an elevation of 3800 m above mean sea level (amsl). The GRV-0 segment extends from Gaumukh to Haridwar (the emergence point of the river into the Ganga alluvial plain) characterised by long stretches of deep gorges alternating with alluvium filled broad valley (Fig. 4A). The Bhagirathi River cuts through the lesser and higher Himalayas in a deep valley and joins the Alaknanda River at Devaprayag. From this confluence, the combined stream is known as the Ganga River.

In this segment, the average river slope is about 1280 cm/km. Five to six levels of unpaired or rarely paired terraces, occurring between 50 to 250 m above the river bed are present in certain part of the valley. Evidences of glacial deposits are recorded up to a height of 1100 m amsl. Much of the sediments are added by mass-wasting process along the steep valley slope. For 300 km from its source, the river drains nearly an area of 23,051 km^2 in the Himalaya (Fig. 4B). The river emerges onto the Ganga alluvial plain at Haridwar at an elevation of 300 m amsl with prominent braided channel

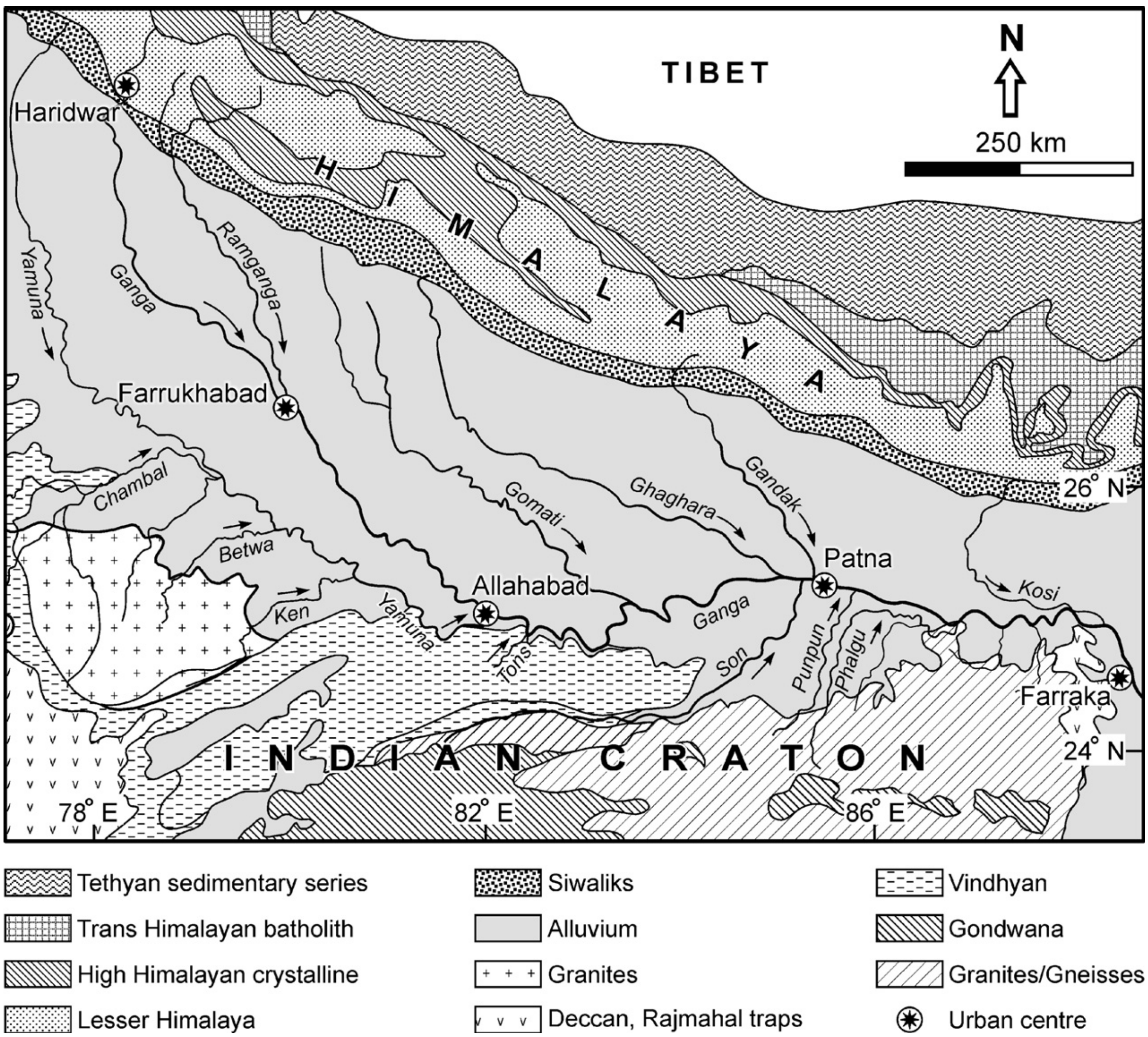

Fig. 3. Geology and drainage network of a part of the Ganga River basin showing major litho-units and tributaries of the Himalaya orogenic belt, the Ganga alluvial plain, and northern Indian craton regions.

characteristics and gravely bars as shown in Fig. 4C and D, respectively.

The GRV-I: Downstream of Haridwar, the Ganga River flows through a 2–35 m deep and 2−40 km wide alluvial valley cut into the regional surface of the Ganga alluvial plain. The GRV-I is characterised by a broad, straight, trending southward valley margins with 10–30 m high cliffs. The river valley terrace (T_1) is prominent, located 2–8 m above the active channel and shows swamps, lakes, and yazoo-type channels. The active channel is 1–3 km wide in flood discharge, braided with huge sandbars mostly 100–500 m wide and 0.5–5.0 km in length. The river slope is 171 cm/km and drops to 33 cm/km in distal part.

The GRV-II: This part extends from Garhmuktesar to Allahabad, a distance of about 610 km in NW–SE direction. The slope varies from 25 cm/km in its upper part to 6 cm/km in its lower part, with an average of

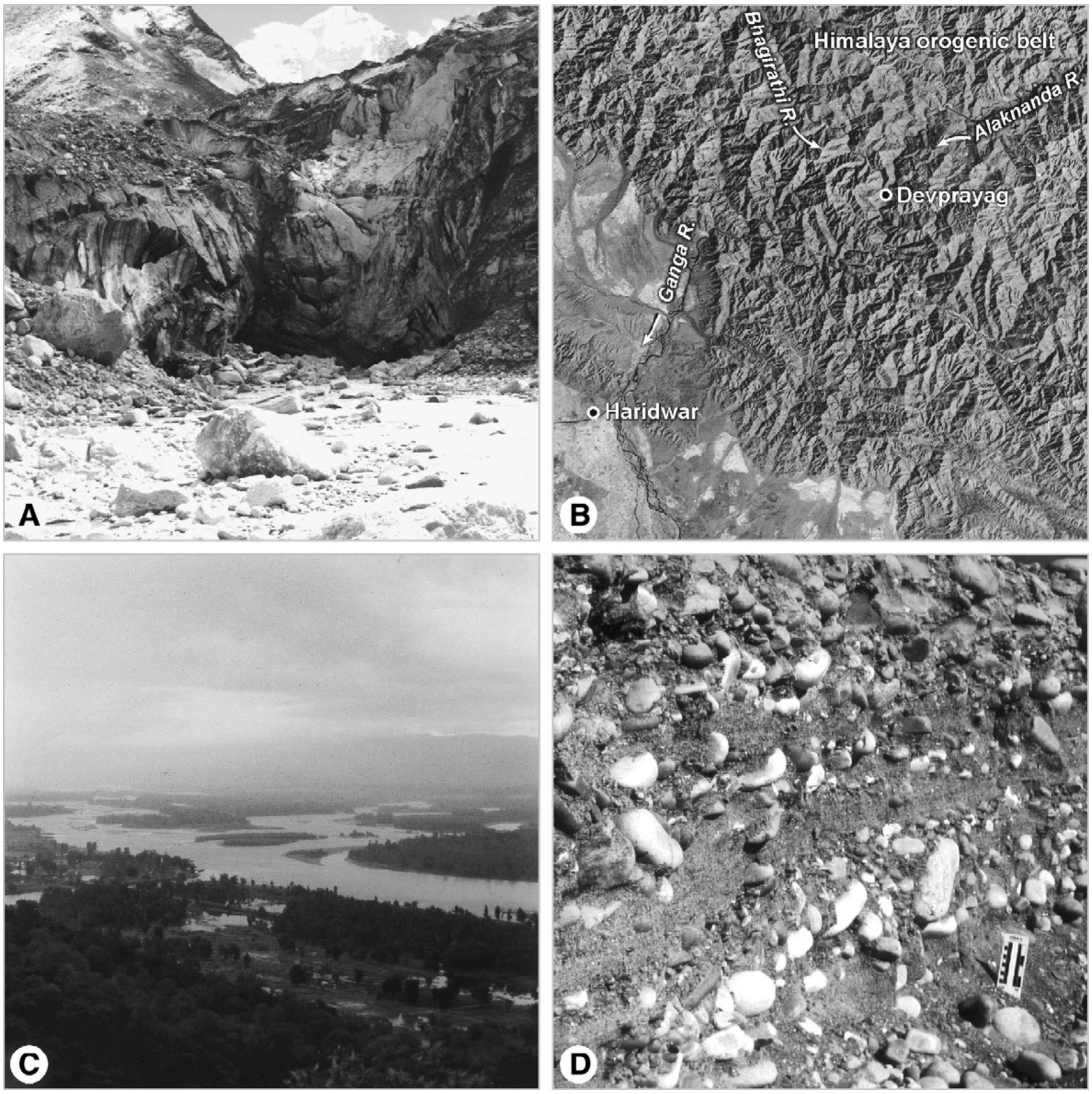

Fig. 4. (A) The Ganga River originates from the snout of Gangotri Glacier (called Gaumukh) under the name of Bhagirathi River at an elevation of 3800 m amsl (The view is upstream. Photo courtesy: R. Bali.), (B) Satellite image showing the Ganga River entering the Ganga alluvial plain at Haridwar after draining 32,300 km^2 in the Himalayan region. The braided channel of the Ganga River is also seen downstream of Haridwar (The image width covers about 80 km.), (C) The Ganga River showing a braided channel pattern after emerging from the Himalaya (The view is downstream of Haridwar.) and (D) An exposed mid-channel bar showing about a 1-m-thick sequence of bedload sediments of the Ganga River deposited before entering the Ganga alluvial plain at Haridwar (The view is upstream.).

16 cm/km. The valley segment is further divided into three sub-segments (A, B, and C). The GRV-IIA is a 10−20 km broad valley that extends up to Kannauj. The Ramganga River, the first major Himalayan tributary, joins the Ganga River from the left at Farrukhabad. The active channel swings from one margin to other margin and shows braided channel characteristics with huge braid bars. The GRV-IIB extends from Kannauj to Baksar with a relatively broad valley of 20−30 km with prominent, discontinuous, 5–20 m high cliffs on the right (southern) margin and about 5 m high cliffs on the left (northern) margin. The river flows along the right

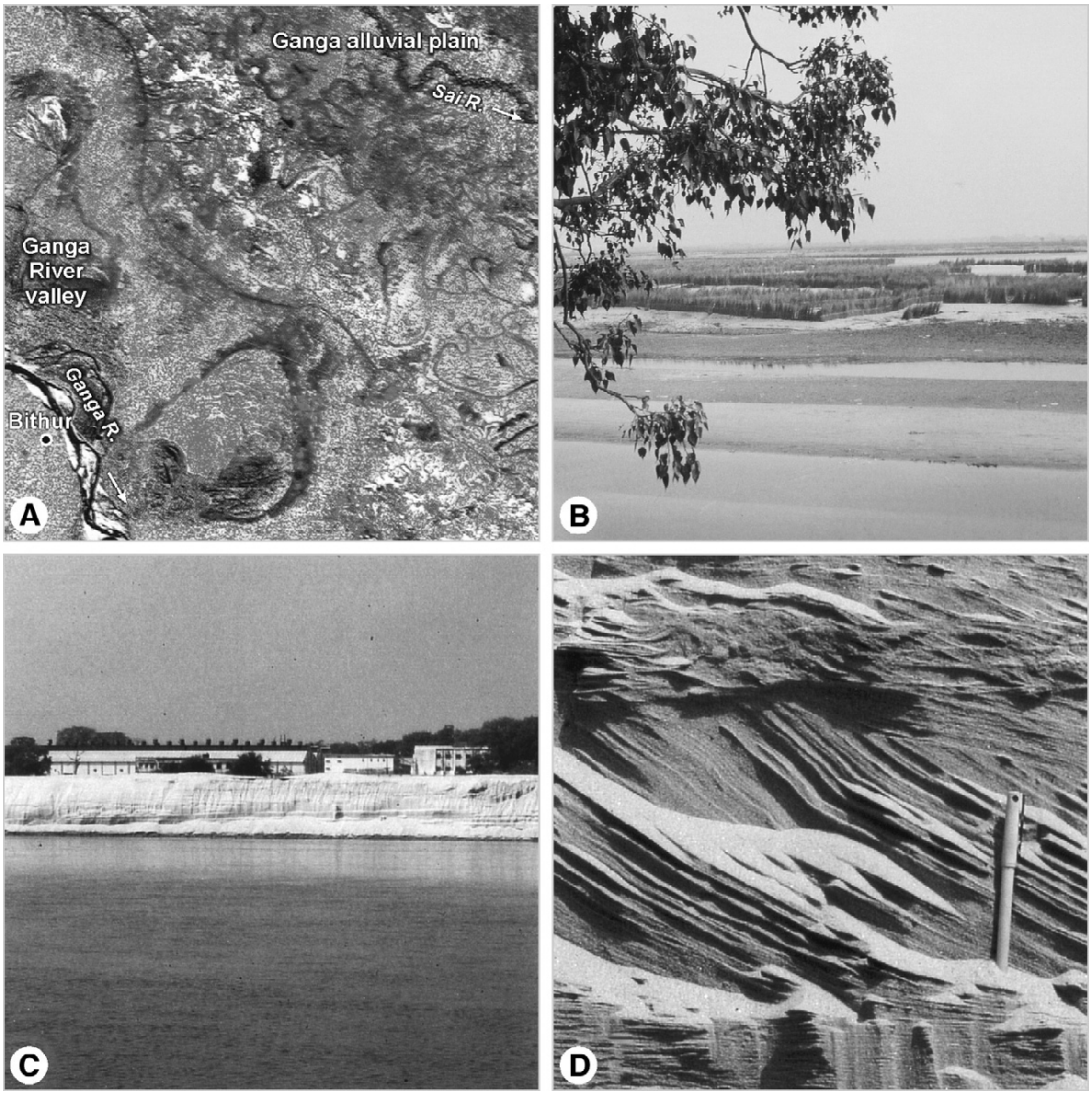

Fig. 5. (A) Satellite image showing an isolated large meander scar in the GRV-IIB segment at Bithur. The braided channels and sand bar assemblage of the Ganga River are also seen (The image width covers about 45 km); (B) Transverse view of the Ganga River valley from the right bank at Bithur. The exposed mid-channel sand bar is a quasipermanent feature of the channel (The view is across the active channel); (C) The vertical accumulation of cross-bedded fine sand channel deposits of the Ganga River exposed during the summer season near Kanpur. It was attributed to the deposition of bedload of the river by migrating sand dunes during the early retreating phase and exposed above the water level as a result of rapid migration of the river's thalweg during the late retreating phase of the monsoon flood cycle. These processes are active throughout the channel length of the river in the Ganga Plain (The view is across the active channel.); (D) An exposed mid-channel bar at Kanpur showing horizontal stratification followed by steeply dipping foresets in the middle and climbing ripple laminations on the top. It is a characteristic display of transition from the upper flow regime to the lower flow regime. These bedforms were developed in the high river stages during the monsoon and become exposed when the river stage falls to its minimum during the summer. Area shown is 40 cm wide. Flow direction is from left to right.

margin of the valley, leaving a broad asymmetrically developed T_1 terrace and isolated meander scar of 20 km wavelength (Fig. 5A, B). The braid bars show prominent bedding sequences (Fig. 5C, D). The GRV-IIC extends from Baksar to Allahabad. The valley is rather narrow, only 1−5 km wide. 15−20 m high cliffs are present on either side. The river swings from one margin to other, usually as a single channel. Large point bars and lateral bars are prominent. The river valley terrace (T_1) is poorly developed.

The GRV-III: At Allahabad, the Ganga River receives its biggest tributary, the Yamuna River from the right and becomes the axial river of the Ganga alluvial plain. This part of the valley is basically lineament controlled and extends from Allahabad to Buxar. It is farther divided into two sub-segments (A and B). In the GRV-

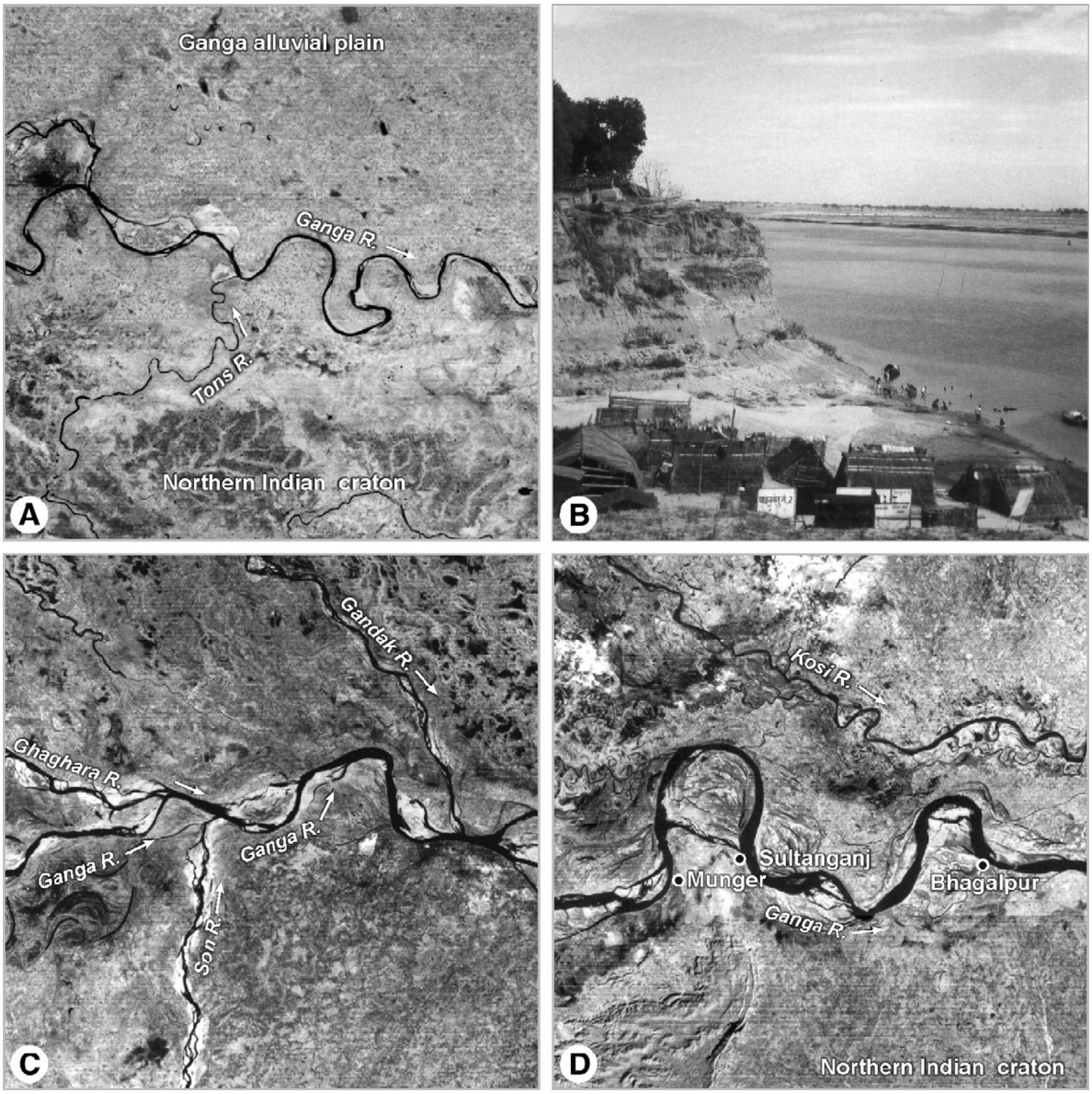

Fig. 6. (A) Satellite image showing the GRV-IIIA segment (downstream of Allahabad). The single sinuous channel and sand bar assemblages of the Ganga River are seen. The perennial tributary (Tons River) and several ephemeral streams are transporting coarser bedload sediments than the Ganga River (The image width covers about 80 km); (B) A 20-m-high escarpment is present on the right valley margin of the GRV-III segment at Kachhwa. It controls the lateral migration of the Ganga River. The river flows toward the right; (C) Satellite image showing the GRV-IV segment characterised by the confluence of the Himalayan and the cratonic rivers. The single sinuous and braided channels and sand bar assemblage of the Ganga River are also seen (The image width covers about 80 km.); (D) Satellite image showing a large free meander developed by the Ganga River at Munger in the GRV-V (The image width covers about 80 km.).

IIIA segment, the Ganga River is oriented W–E with a slope of 16 cm/km and drains very close (only a few tens of kilometres or at very shallow depths) to the margin of the northern Indian craton. The Tons, another small tributary of the northern Indian craton, joins the Ganga on the right (Fig. 6A). At Chunar, basement rocks crop out on the right bank of the Ganga River. The valley is narrow and sinuous boarded by high cliffs often present on both margins. The 300-km-long GRV-IIIB segment is a 2−10 km wide valley with 10−30 m of incision and WSW–ENE orientation. The Gomati, an alluvial river of the Ganga alluvial plain, joins the Ganga from the left margin. The valley is narrow and sinuous with meandering channel. The T_1 terrace is developed mostly on one side and alternating with meanders (Fig. 6B).

The GRV-IV: This segment is 200 km long, extending from Buxar to Barh. The valley is 20−35 km wide with margins of 2−5 m high cliff. The active channel is mostly present in the middle part. Just upstream of Patna, the Ganga receives two tributaries the Ghaghara and the

Fig. 7. (A) Second-order meandering channel following curvature of the thalweg at a time of falling stage of the Ganga River at Bhagalpur (The view is downstream.); (B) An isolated rock exposure of the northern Indian craton region near the right bank of the Ganga River at Kahalgown (The view is upstream.); (C) The Bhagirathi River, a single meandering delta distributary channel, at Katwa in the western Ganga–Brahmaputra delta region (The view is upstream.); (D) Satellite image showing the lower Meghna River in the eastern part of the Ganga–Brahmaputra delta region along with numerous sand islands in the Bay of Bengal (The image width covers about 80 km.).

Gandak Rivers from the left and the Son River from the right (Fig. 6C). The Ganga River enlarges enormously in response to the contributions from these tributaries. The valley terrace (T_1) is prominent and shows many meander scars, linear lakes and small channels.

The GRV-V: The 305-km-long valley segment is located upstream of the delta plain between Barh and Farraka. In this segment, the river shows an extensive development of valley, almost 20−30 km wide with W–E orientation and an average slope of 6 cm/km. Tributaries from the right are the Punpun and the Phalgu Rivers. Near the right bank, the Phalgu River flows for almost 100 km parallel to the Ganga River, before its joining. It receives the Kosi River from the left. At Sultanganj and Kahalgaon, basement rocks of the northern Indian craton are exposed within the channel pointing to shallow depth of the alluvium (Fig. 7B). The Ganga swings around the Rajmahal Hills and flows almost due south to enter into its delta region at Farraka. The active Ganga channel in this segment is highly sinuous, making large meander loops

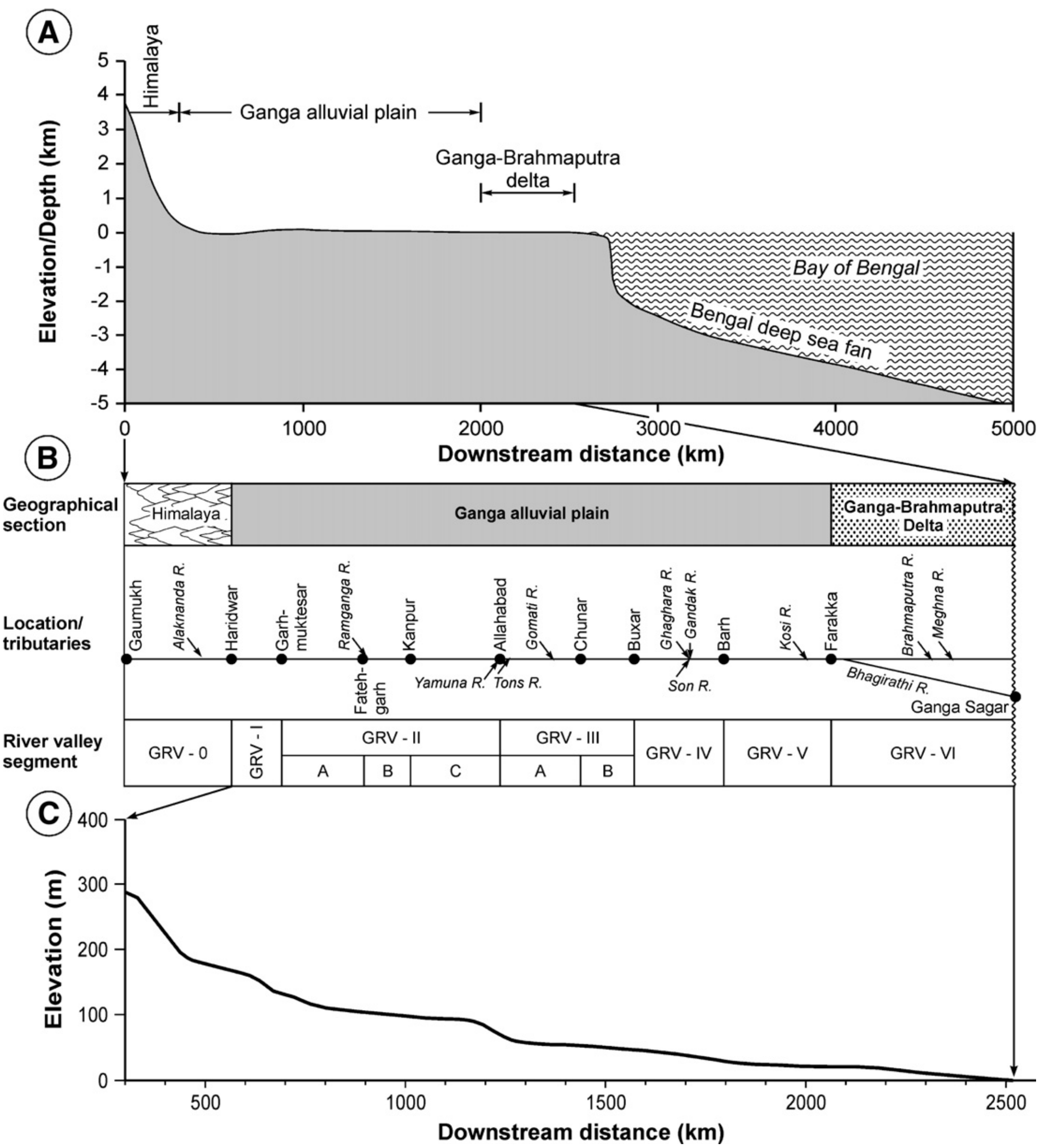

Fig. 8. (A) Topographical profile along the Ganga River showing relief features of the Indian subcontinent and the Bay of Bengal along the active channel. (B) Longitudinally, the Ganga River valley is divided into the seven segments (GRV-0 to GRV-VI). (C) Longitudinal profile of the Ganga River (downstream of Haridwar) acts as a pathway to disperse the sediments from source to sink.

that exhibit prominent curvature close to the left valley margin (Fig. 6D). Within the channel, huge sand bars, tens of kilometres in length are often traversed by relatively large secondary channels. This segment is characterised by maximum fluvial discharge that make the sandbars and active channel unstable and modified by the flood discharges (Fig. 7A).

The GRV-VI: This segment represents the delta region of the GRB. At Farraka, a delta distributary branches off from the right bank of the Ganga and is known as the Bhagirathi River that flows toward the south through Calcutta. The river slope is 4 cm/km. The tidal influenced reach of the Bhagirathi is known as the Hugli River (Fig. 7C). Downstream of Farraka, main channel of the Ganga River, after joining of the Brahmaputra River, flows down to SE as the Padma River. It is known as the Meghna River before falling into the Bay of Bengal (Fig. 7D).

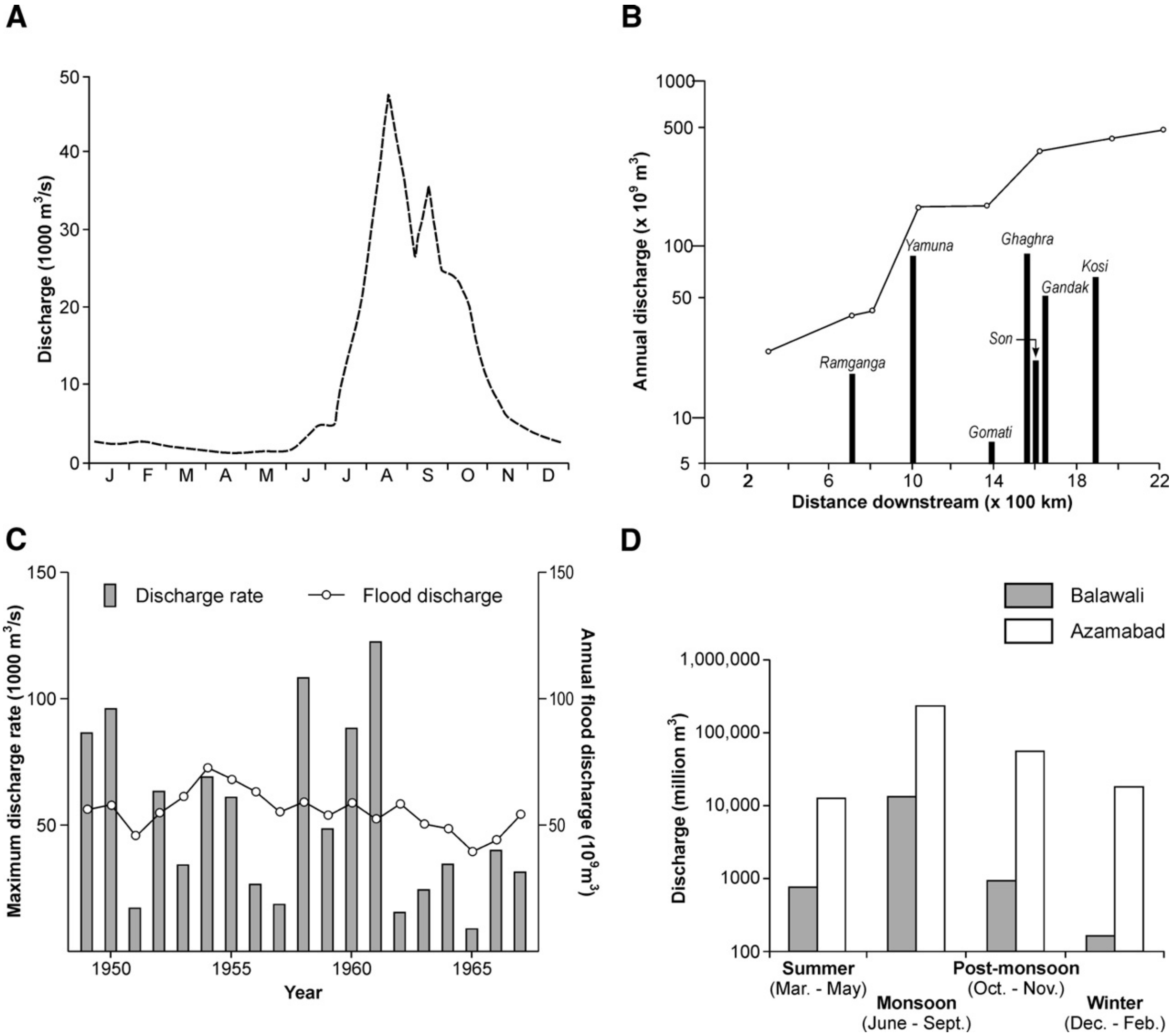

Fig. 9. Hydrology of the Ganga River is characterised by its extreme seasonality as a consequence of summer monsoon. (A) The annual hydrograph characterised by low flows during post- and pre-monsoon seasons and extremely high flows during the monsoon season (after Rao, 1975). (B) Downstream increase in the annual discharge of the Ganga River because of contributions from its tributaries before entering into the delta region (data source: Rao, 1975); (C) The annual variability in maximum flood discharge rates and volumes of the Ganga River for 19 years based on data from UNESCO (1976). These floods cause the extensive overbank flooding and result in the enormous spontaneous transportation of the Ganga River sediments to the Bay of Bengal. (D) Seasonal variation in discharge of the Ganga River at Balawali and Azamabad before entering the Ganga alluvial plain and the Ganga–Brahamaputra delta areas, respectively (data source: Das Gupta, 1984). [See Fig. 8 for location of the gauging stations].

Table 1
Hydrological characteristics of the Ganga River at Haridwar after draining an area about 23,051 km^2 in the Himalaya (after Das Gupta, 1975)

Season	Period	Discharge (m^3/s)	Runoff ($\times 10^6$ m^3)	Flow (in %)
Monsoon	June–September	1523	15,952	75
Post-monsoon	October–December	308	2447	11
Winter	January–March	194	1507	7
Summer	April–May	282	1487	7
Year		678	21,393	100

2.6. Longitudinal profile

Fig. 8 displays the longitudinal profile of the Ganga River within alluvial plain with the GRV divisions. The river profile is typically L-shaped and represents gradients of each of its reaches as an action to tectonic, lithologic, and climatic factors. The gradient in the Himalayan stretch is steep (1280 cm/km). It decreases drastically downstream in the Ganga alluvial plain (16 cm/km) and becomes very low in the delta reach (5 cm/km). The Himalayan, the alluvial plain, and the delta reaches of the profile are very distinct and can be characterised by physical erosion, fluvial transportation, and deposition processes, respectively. Convexities visible in the longitudinal profile in the GRV-IIA and GRV-IIIA segments indicate subsurface tectonic activity (Singh, 2001).

2.7. River hydrology

The Ganga River is a tropical monsoon river. Its annual hydrography is characterised by low flows during the post- and pre-monsoon seasons and by extremely high flows during the monsoon season from heavy rainfall. The flood cycle is very peaked and indicates a rapid increase in the discharge during July and the first half of September. The rate of the rise and fall of the river discharge is rapid and generally uniform (Fig. 9A).

At Haridwar, the river annually discharges 21,393 × 10^6 m^3, of which 75% flows during the monsoon period (June to September) and 25% is distributed during the remaining part of the year (Table 1). The average discharge of the river is over 1523 m^3/s during the monsoon period and decreases to 282 m^3/s in winter. Every year, normal flood discharge shoots up to 5860 m^3/s. Farther downstream at Garhmuktesar, flood discharge is even higher up to 8500 m^3/s because of significant contributions by several small tributaries (such as the Malin, the Chhoiya and the Solani rivers) draining the nearby area of the Siwaliks and alluvial plain (Das Gupta, 1975). The discharge increases from Haridwar to Farraka eighteen fold because of significant contributions from its tributaries, namely from the Yamuna, the Ghaghara, the Kosi, the Gandak and the Son Rivers (Fig. 9B). Table 2 presents the hydrological characteristics of the Ganga River at various locations in the Ganga alluvial plain region. Nandargi and Dhar (1998) observed that active monsoon conditions prevailing over the alluvial plain for a fairly long period (10 d), and 'Monsoon break' situations over the Himalaya are responsible for heavy to very heavy rainfall in the GRB. With the results, floods occur almost simultaneously in the Ganga River and its tributaries. Fig. 9C depicts the annual variability of maximum flood discharge rates and volumes of the Ganga River for 19 years (UNESCO, 1976). These flood discharges observed for a few days (mostly less than a week) account for nearly 50% of the normal annual runoff. Table 3 presents the hydrological characteristics of the Ganga

Table 2
Seasonal flow variation and maximum discharge at various downstream stations of the Ganga River in the Ganga River Valley (after Das Gupta, 1984)

Downstream stations	Mean seasonal flow ($\times 10^6$ m^3)					Maximum discharge observed m^3/s (yr)
	Monsoon (June–Sept.)	Post-monsoon (Oct.–Dec.)	Winter (Jan.–March)	Summer (April–May)	Total flow	
Balawali	13,306	947	167	760	15,180	–
Garhmuktesar	18,392	1756	908	982	22,038	6940 (1978)
Fatehgarh	17,300	1266	264	281	19,111	–
Kanpur	30,763	4139	1518	910	37,330	14,071 (1961)
Allahabad	112,278	10,703	4148	2987	130,116	58,377 (1971)
Mirzapur	97,142	9362	4529	3362	114,395	–
Varanasi	112,206	11,244	4213	2793	130,456	46,186 (1971)
Buxar	113,247	17,741	5463	3438	139,889	43,084 (1969)
Patna	192,625	28,488	11,044	8341	240,498	65,849 (1978)
Azamabad	235,357	54,494	18,055	12,474	320,380	83,047 (1971)

Table 3
Hydrological characteristics of the Ganga and other rivers in its delta region (after Julien, 2002)

River	Mean annual discharge (m^3/s)	Bankfull discharge (m^3/s)	Channel width (m)	Depth (m)	Velocity (m/s)
Ganga	11,000	43,000	3700	6.5	1.78
Brahmaputra	20,000	48,000	4200	6.6	1.70
Padma	28,000	75,000	5200	7.5	1.93

and other rivers in the delta region. These bankfull discharges result in an enormous spontaneous transportation of sediments to the Bay of Bengal along with changes in the river channel morphology. Fig. 9D shows the seasonal variation in discharges exhibiting changes by a factor of 10 to 100 times in the Ganga River. At Farraka, the extreme flood discharge of 72,915 m^3/s is 1.31 time higher than the mean annual flood discharge.

The Ganga River experiences a rapid downstream increase in discharge due to significant inputs from its tributaries and plays an ineffective role in morphological processes in the GRV due to very low channel gradient along with a large channel width. This can be expressed by unit stream power obtained by considering the values of channel width, channel slope, monsoon discharges, and specific weight of water. Table 4 presents the unit stream power of the Ganga River at various locations for understanding of sediment transportation ability during monsoon season.

2.8. River sediments

A river derives its sediments from several sources distributed throughout its drainage basin and transports them in a wide range of grainsize. Major sediment sources of the Ganga River namely the Himalaya orogenic belt, the Ganga alluvial plain and the northern Indian craton regions are topographically and geologically distinct in nature. The river supplies vast quantities of sediments from the erosion of the Himalaya orogenic belt and the northern Indian craton regions, slope erosion of the Himalayan foothills, and sheet erosion of the Ganga alluvial plain. Consequently, the Ganga carries a heavy sediment load of around 729×10^6 tons annually (Milliman and Meade, 1983). The erosional rates are highest in the high Himalaya at 2.7 mm/yr and about 0.8 mm/yr in the lesser Himalaya (Vance et al., 2003). Recently published data of Nd/Sm tracer studies also suggested that the higher Himalaya is the main source of sediments to the Ganga River (Wasson, 2003).

Table 5 presents the sediment load of the Ganga River at Hardinge Bridge and Goalundo during the low, rising, flood, and falling stages of flow regimes. The river transports suspended load slightly over 6.5×10^6 tons/d at peak flood stage. In comparison to the low stage, sediment load and water discharge of the Ganga River increase in the flood stage by a factor of >25 and >45, respectively. After joining the Brahmaputra River, the total estimated combined sediment flow to the Bay of Bengal is 1620×10^6 tons annually. If 1000×10^6 tons/yr is an accurate estimate of suspended load, then 620×10^6 tons/yr of the total is the bedload (Wasson, 2003). From the sink point of view, the total sediment load has been almost equally partitioned in the Bay of Bengal, with thirds of the total load each being deposited in the subaerial delta, the subaqueous delta, and the deep sea fan regions (Goodbred and Kuehl, 1999).

Table 4
Estimation of unit stream power for certain stations in valley segments of the Ganga River[a]

River valley segments	Location	Mean monsoon discharge (m^3/s)	Channel width (m)	Channel slope	Unit stream power (W/m^2)
GRV-0	Devprayag	1775	55	0.003	948.8
GRV-I	Haridwar	5860	500	0.00171	196.4
GRV-I	Balawali	3898	1000	0.00150	57.3
GRV-IIA	Garhmuktesar	5800	400	0.00030	42.6
GRV-IIB	Kanpur	6317	1000	0.00016	9.9
GRV-IIIA	Allahabad	24,131	750	0.00016	50.4
GRV-IIIB	Varanasi	21,262	400	0.00012	62.5
GRV-IV	Patna	37,424	2000	0.00005	9.2
GRV-V	Azamabad	49,968	2400	0.00006	12.2
GRV-VI	Farraka	55,776	2500	0.00005	10.9
GRV-VI	Padma River	75,000	5200	0.00005	7.1

[a] Specific weight of water = 9800 N/m^2; data: from several sources.

Table 5
Suspended sediment load characteristics of the Ganga River in its delta region (after Coleman, 1969)

Location	Date/month	Flow regime	Sediment load ($\times 10^6$ kg/d)
Paksay	June	Rising stage	830
	July	Rising stage	3170
	August	Flood stage	6630
	September	Falling stage	4370
Goalundo (Ganga channel only)	24-04-66	Low stage	308
	06-06-66	Rising stage	1135
	21-06-66	Rising stage	2500
	04-07-66	Rising stage	4400
	11-08-66	Flood stage	7800
	14-09-66	Flood stage	8200
	29-09-66	Falling stage	3600

3. Objectives

The primary objective of this study is to investigate bedload and suspended load sediments of the Ganga River by obtaining complementary insight into their textural properties, grainsize characteristics, and transportation dynamics. First, we will discuss the textural composition and the Folk and Ward (1957) grainsize parameters (mean, standard deviation, skewness, and kurtosis) and their interrelationships and their downstream changes. Secondly, channel hydraulics, grainsize images, and channel bedform sequence of the river are used to comprehend the sediment transportation dynamics for a better understanding of the monsoon-controlled fluvial system.

4. Methodology

In a river, bedload sediments comprise rolling, sliding, and saltating grains moving on or near the river bed. Suspended load sediments comprise those grains transported completely within, and supported by, a turbulent flow at local flow velocities. Several field and flume studies have indicated that grainsize distribution in sediments of a river bed subsurface is similar to the river's bedload. Dietrich et al. (1989) proposed that the disparity between mean grainsize of river bed subsurface sediments and bedload sediments can arise from imbalances between transportation and supply rate, affecting a small part of the river bed or the entire river bed.

Sediment samples collected from the subsurface of a river's active channel were classified as bedload sediments, whereas sediment samples collected form the top of sandbars or from an overbank were classified as suspended load sediments. The downstream distance from the source (Gaumukh) of the Ganga River is used to identify the GRV segments and sample locations. The upper part of the Ganga River segment (Haridwar to Allahabad) represents a common source for sediments derived from the Himalaya orogenic belt and the Ganga plain regions, and the lower part of the river segment (Allahabad to Farraka) represents sediments derived additionally from the northern Indian craton region of the GRB.

4.1. Site selection

For sampling of bedload and suspended load sediments, care has been taken in site selection for sample consistency associated with uniform flow regime and a particular sediment transportation environment. Sampling stations were selected on exposed riverbeds on the basis of their location (accessibility at intervals of 20 to 50 km). All the sampling was carried out in May and June 1990 during the low flow stage of the river.

In all, 53 sampling locations (G1 to G53) of the Ganga River, four locations (H1 to H4) from its delta distributary, and six locations (T1 to T6) from its tributaries were selected. Out of these 53 locations, 11 are from GRV-I, 16 from GRV-II, 12 from GRV-III, 3 from GRV-VI, and 11 from GRV-V (Fig. 10). From each location, three bedload sediment samples were collected. For suspended load sediments, one sample each was collected from 27 locations (G5, G6, G7, G11, G12, G13, G15, G16, G17, G18, G22, G24, G25, G28, G29, G30, G31, G33, G36, G38, G39, G42, G43, G44, G45, G46, and G52). All locations were carefully chosen to avoid contamination from the riverbank materials or from anthropogenic reworking.

4.2. Sampling method

Sediment samples were collected from exposed, freshly developed depositional sequences (lateral, mid-channel or point bars, floodplain or natural levee) close to the active channel and its margins. Locating these units in summer (pre-monsoon seasons) is relatively easy as the active channel cuts its own sediment bars and flows at lower levels because of very low discharges. Sequences of a few metres thick channel deposits are exposed above the low water level near the active channel (Fig. 5C). Three samples were collected at a depth of 0.5−1.0 m from different places of each sampling station to get "representative" data for the bedload sediments of that station.

4.3. Grainsize analysis

Bedload samples were dried in an electric oven at 45 °C. About 100 g of the sample was used for the dry sieve analysis at 1/4 Φ intervals by ASTM (American Society for Testing and Materials) sieve mesh numbers 8, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 100, 120, 140, 170, 200, and 230. For the suspended load sediment samples, about 20 g of the dried samples was re-suspended for several hours in distilled water. These subsamples were further sonicated two to three times for 30 s. These suspended sediment solutions were segregated into 200, 63, and 20 μm teflon nylon sieves. The sieved fractions were collected in clean porcelain bowls and were dried at 45 °C. The dried sediment fraction was again weighted to determine the grainsize distribution of sediment fractions >200, 200−63, 63−20, and <20 μm by weight percentage.

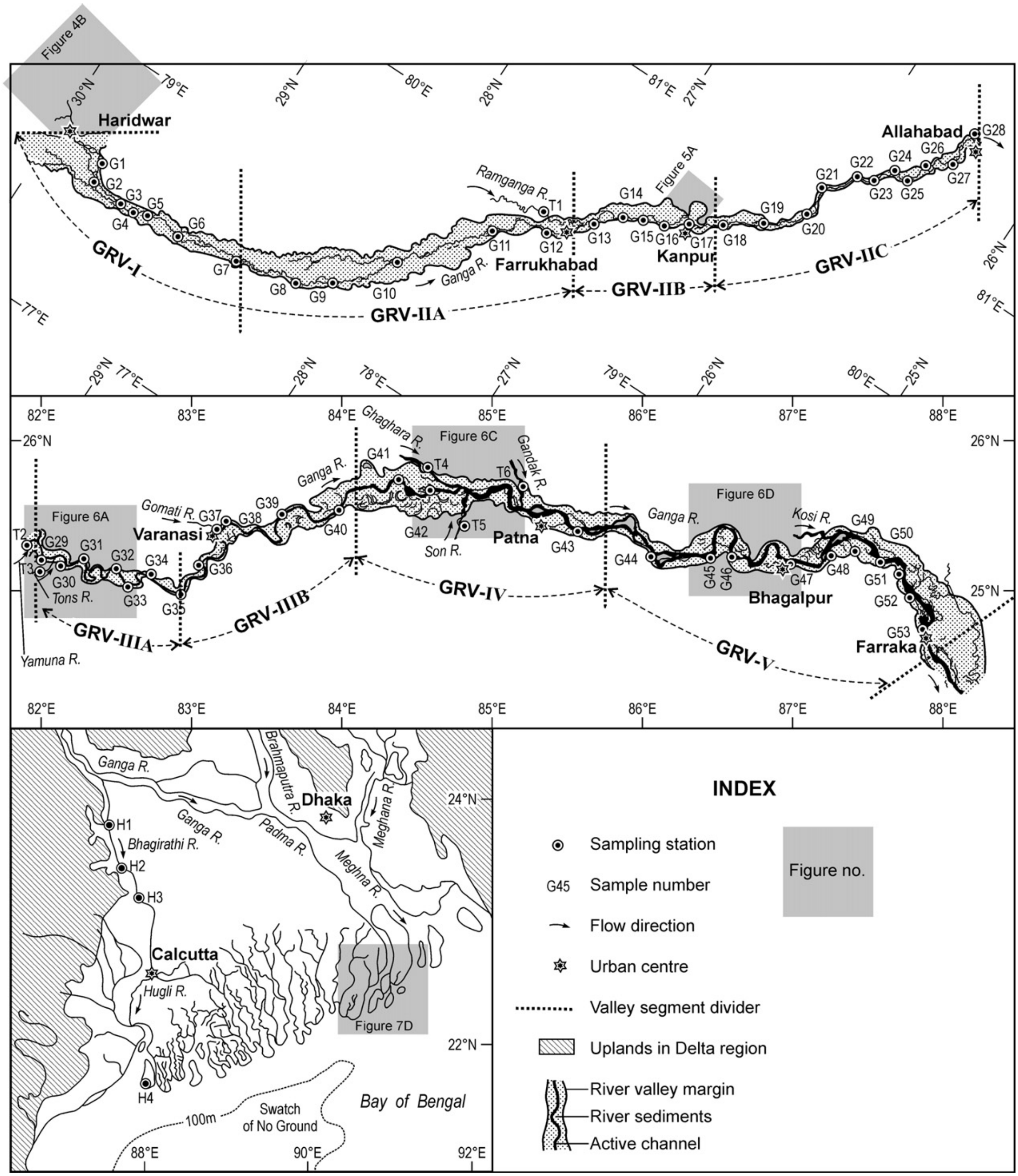

Fig. 10. Location map of sampling stations on the Ganga River: G1—Nagal; G2—Balawali; G3—Mirapur; G4—Daranagar Ganj; G5—Jamail Ganj; G6—Hastinapur; G7—Garhmuktesar; G8—Anupshahar; G9—Ramghat; G10—Kachhla; G11—Shamshabad; G12—Farrukhabad; G13—Kannauj; G14—Araul; G15—Bilhaur; G16—Radhan; G17—Bithur; G18—Kanpur; G19—Bakser; G20—Gagauso; G21—Dalmau; G22—Tir ka purwa; G23—Kalakankar; G24—Manikpur; G25—Kara Gutani; G26—Jahanabad; G27—Purwamufti; G28—Allahabad; G29—Manaiya; G30—Sirsa; G31—Lachhagir; G32—Gopiganj; G33—Vindhyachal; G34—Kachhwa; G35—Chunar; G36—Varanasi; G37—Kaithi; G38—Saidpur; G39—Ghazipur; G40—Buxar; G41—Rudrapur; G42—Dighwara; G43—Barh; G44—Mokama; G45—Munger; G46—Sultanganj; G47—Bhagalpur; G48—Kahalgown; G49—Sahibganj; G50—Sakari Gali; G51—Maharajpur; G52—Rajmahal; and G53—Farraka. The Ganga River tributaries: T1—Ramganga River (Farrukhabad); T2—Yamuna River (Allahabad); T3—Tons River (Manaiya); T4—Ghaghara River (Manshi); T5—Son River (Kailwar); T6—Gandak River (Hazipur). In the Ganga–Brahamaputra delta region, H1 to H4 are sampling stations on the Bhagirathi River.

Weight percentage of each size fraction was calculated using the Phi-scale (Φ) to grade and classify these sediments. The cumulative frequency plots were made on a log-probability paper, and Φ values at 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles were obtained from the plot. Statistical parameters were calculated using the method of Folk and Ward (1957) as follows:

Graphic mean: $(\Phi_{16}+\Phi_{50}+\Phi_{84})/3$
Inclusive graphic standard deviation: $(\Phi_{84}-\Phi_{16})/4+(\Phi_{95}+\Phi_{5})/6.6$
Inclusive graphic skewness: $\{(\Phi_{16}+\Phi_{84}-2\Phi_{50})/2(\Phi_{84}-\Phi_{16})\}+\{(\Phi_{5}+\Phi_{95}-2\Phi_{50})/2(\Phi_{95}-\Phi_{5})\}$
Graphic kurtosis: $(\Phi_{95}-\Phi_{5})/2.44(\Phi_{75}-\Phi_{25})$where Φ is the unit of grainsize and it is expressed as:

$$\Phi = -\log_2(d/d_0) = -3.3219\ \log_{10}(d)$$

where d_0 is a reference grainsize and it is fixed at 1 mm. The minus sign was introduced in order that sand sizes would have positive Φ numbers. The base 2 logarithms follow the geometric Wentworth size scale.

4.4. Other data sources

Discharge data of the Ganga River were collected from various sources to understand the hydrological characteristics and sediment transportation dynamics (Das Gupta, 1975; Pandey, 1980; Das Gupta, 1984; Julien, 2002). Sediment–water interaction studies by Shukla and Singh (2004) for the Ganga River and Coleman (1969) for the Brahmaputra River have been used as an analogous model of transportation in the Ganga River sediments.

5. Results and discussion

5.1. Sediment characteristics

5.1.1. Textural properties

The Ganga River and its tributaries have their sediment textural characteristics determined by their geologically distinct drainage regions of the GRB. For the bedload sediment studies, the Ganga, the Ramganga, the Ghaghara, and the Gandak Rivers draining the Himalaya orogenic belt region; the Gomati River draining the

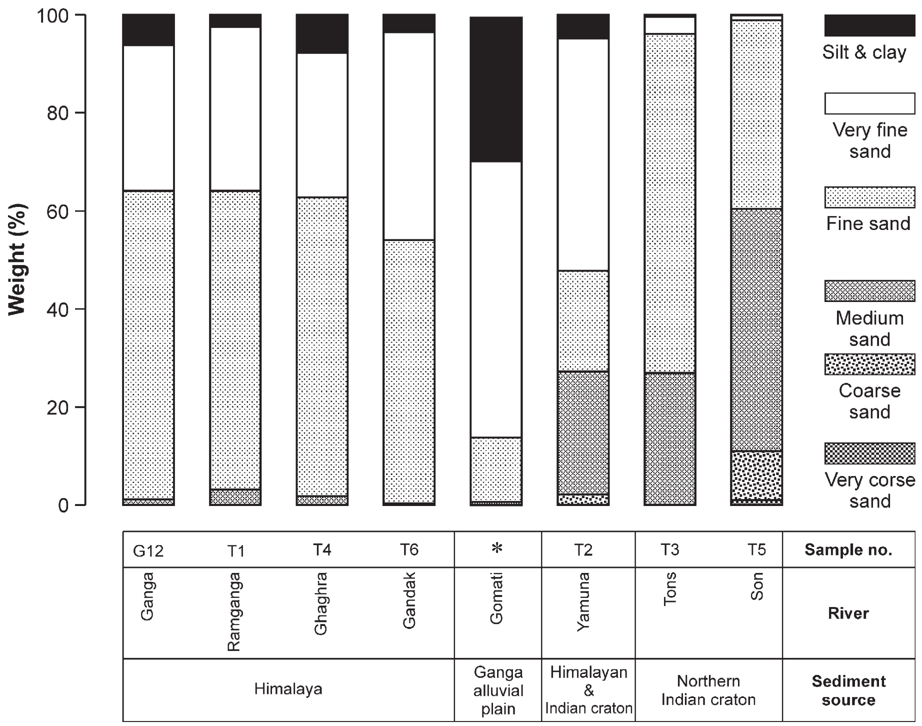

Fig. 11. Bars showing the textural characteristics of bedload sediments of the Ganga River and its tributaries. Rivers draining the Himalaya orogenic belt are characterised by the dominance of fine and very fine sand; the northern Indian craton rivers by medium sand and fine sand; the Ganga alluvial plain river by very fine sand and silt/clay contents. The Yamuna River receives its sediments from the Himalaya and the craton regions. It, therefore, shows an intermediate characteristic. [*Data source of the Gomati River sediments is from Kumar and Singh (1978) and see Fig. 10 for location of the sampling stations].

Ganga alluvial plain region; and the Son and Tons Rivers draining the northern Indian craton region were selected. Fig. 11 displays a bar diagram representing the textural characteristics of bedload sediments of these rivers. Rivers originating from the Himalaya orogenic belt region are characterised by the predominance of fine sand and very fine sand. The rivers draining the northern Indian craton region bring much coarser sediments than the Himalayan rivers and are characterised by the high content of coarse- and medium-grained sand. The Ganga alluvial plain rivers carry finer bedload sediments than from the other two regions namely very fine sand, as they recycle the Himalayan-derived sediments of the Ganga alluvial plain. The above variations clearly indicate the importance of source area in textural characteristics of bedload sediments. McLaren (1981)

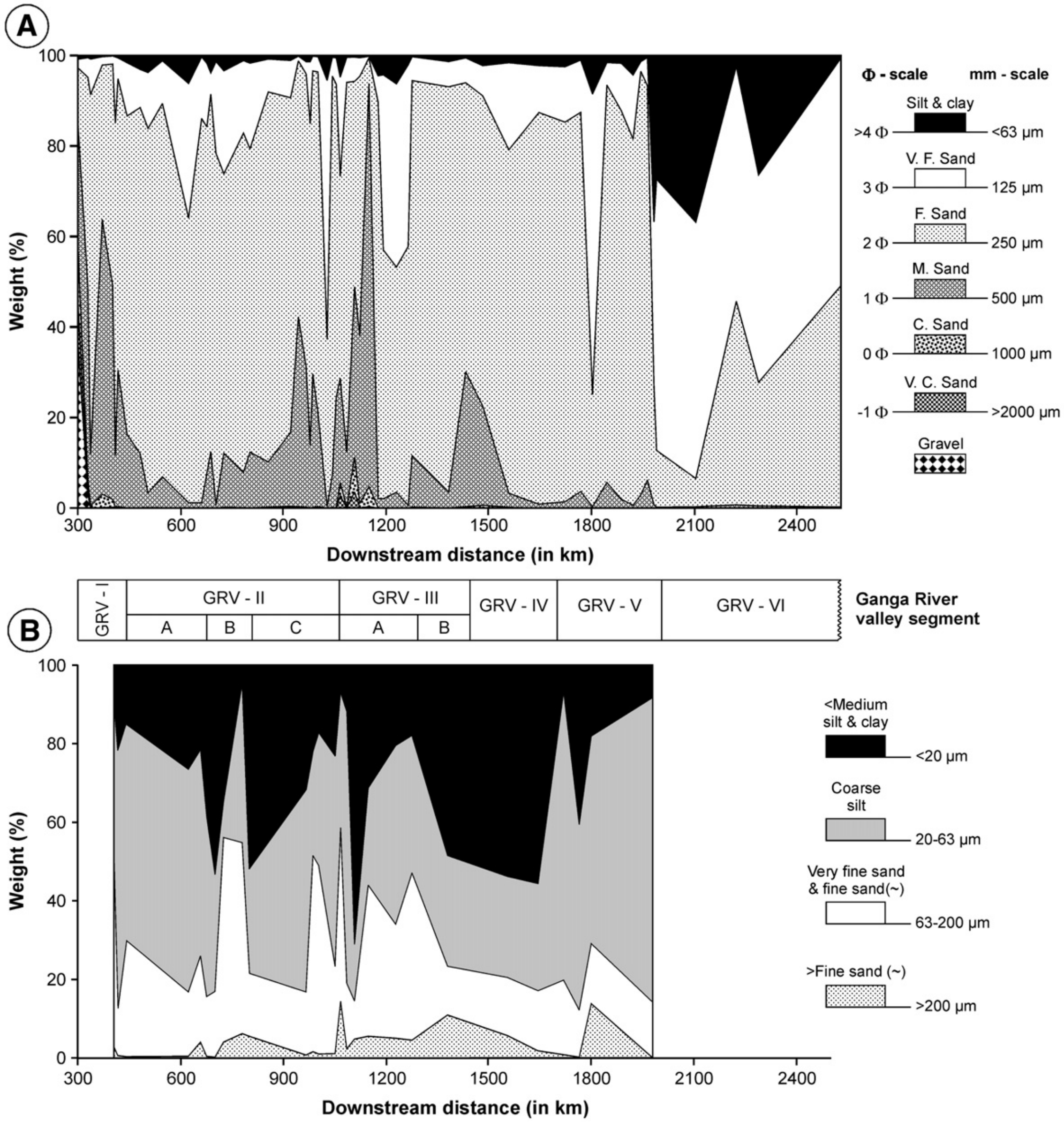

Fig. 12. (A) Downstream variations in weight percent of various grainsize fractions in bedload sediments of the Ganga River. The downstream decrease followed by increase in medium sand and very fine sand contents in the upper Ganga River displays selective sediment transportation phenomena. The coarse sediment fraction in the middle river valley segment (GRV-III) indicates sediments inputs by tributaries draining the northern Indian craton region. (B) Downstream variation in weight percent of various grainsize fractions in suspended load sediments of the Ganga River. The coarse silt fraction generally shows increase toward the delta region. The Ganga River valley segments are shown for reference.

also argued that grainsize characteristics of sediment are controlled more by the nature of the source area than by the transportation process or depositional environment. The Ganga River tributaries play a significant role in downstream changes in textural characteristics of the Ganga River sediments.

The longitudinal grainsize distribution of the bedload sediments has been presented by the textural diagram in Fig. 12A. It is characterised by a sharp gravel–sand transition and sand–silt transition developed while entering into the Ganga alluvial plain and the delta regions, respectively. There is a close correlation between the occurrence of gravels and the occurrence of very coarse sand. The fine sand and very fine sand contents, therefore, are the dominant grainsize fraction in the plain and the delta regions, respectively. The proportion of silt and clay fractions (values >4.0 Φ) varies from 0.1 to 8.5% in the river and reaches a value of 36.8% in the lowermost valley and the delta regions. Medium sand and fine sand show downstream variability controlled by selective hydraulic sorting and tributary input. The longitudinal grainsize distribution of the suspended load sediments is presented by the textural diagram in Fig. 12B. In the suspended load sediments, the proportion of coarse silt sediment fraction (63–20 μm) varies from 9.2 to 77.5%.

5.1.2. Grainsize parameters

Grainsize parameters (mean grainsize, standard deviation, skewness, and kurtosis) are the fundamental and readily studied features of clastic sediments and deposits of all depositional environments. In the river sediments, these parameters are dependent on sediment grainsize distribution of its source and processes of winnowing, selective deposition of grainsize during transport, and total deposition of sediment in transport (McLaren, 1981). Table 6 displays these grainsize parameters of the bedload and suspended load sediments of the Ganga River, which are discussed in following sections.

5.1.2.1. Mean grainsize. A well-recognised phenomenon of a river system is an exponential decrease in grainsize with downstream distance if there are no lateral inputs of sediments from tributaries and valley sides. Hydraulic sorting and abrasion processes have been considered to explain downstream decrease in grainsize. In hydraulic sorting, finer grains are transported faster and farther than coarse grains. Individual grains are diminished in size during the process of abrasion. Over the past two decades, observations of modern and ancient rivers and of flume studies have significantly increased our understanding of downstream variation in grainsize of a river system. Fluvial

Table 6
Summary giving the ranges and average values in brackets for the Folk and Ward (1957) grainsize parameters in bedload and suspended load sediments of the Ganga River and its tributaries

River	Sampling stations	Mean grainsize (in Φ)	Standard deviation (in Φ)	Skewness	Kurtosis
Bedload sediments					
Ganga River					
GRV-I	G1–G12	1.8–3.0 (2.4)	0.3–0.7 (0.5)	−0.2–0.3 (0.1)	0.9–2.0 (1.3)
GRV-II	G13–G28	2.1–3.3 (2.5)	0.3–0.6 (0.4)	−0.1–0.2 (0.0)	0.9–1.5 (1.1)
GRV-III	G29–G40	1.5–3.1 (2.5)	0.3–0.6 (0.4)	−0.1–0.5 (0.2)	0.8–2.4 (1.4)
GRV-IV	G41–G43	2.4–2.8 (2.6)	0.3–0.5 (0.4)	−0.2–0.3 (0.1)	1.2–2.1 (1.7)
GRV-V	G44–G53	2.4–3.7 (2.9)	0.3–0.5 (0.4)	−0.3–0.5 (0.1)	1.0–1.8 (1.3)
All samples	G1–G53	1.5–3.7 (2.6)	0.3–0.7 (0.4)	−0.3–0.5 (0.1)	0.8–2.4 (1.3)
Tributaries					
Ramganga River	T1	3.0	0.5	0.3	1.3
Yamuna River	T2	2.8	0.4	0.2	1.0
Tons River	T3	2.2	0.3	0.2	1.3
Ghaghara River	T4	3.0	0.4	02	1.7
Son River	T5	1.8	0.6	0.0	1.0
Gandak River	T6	3.1	0.4	0.5	1.0
All samples	T1–T6	1.8–3.1 (2.7)	0.3–0.6 (0.4)	0.0–2.0 (0.5)	1.0–1.7 (1.2)
Suspended load sediments					
Ganga River					
GRV-I	G6–G12	3.4–4.1 (3.9)	0.8–1.1 (0.9)	−0.1–0.2 (0.0)	1.1–2.1 (1.6)
GRV-II	G13–G28	3.1–4.4 (3.9)	1.0–1.5 (1.1)	−0.6–0.4 (0.0)	1.7–4.6 (2.5)
GRV-IV	G29–G39	2.9–5.0 (3.8)	0.8–1.6 (1.3)	−0.3–0.1 (−0.1)	1.0–4.1 (2.9)
GRV-V	G42–G52	3.5–4.8 (4.2)	0.6–1.5 (1.1)	−0.3–0.0 (−0.1)	0.7–3.8 (2.3)
All samples	G6–G52	2.9–5.0 (3.9)	0.6–1.6 (1.1)	−0.6–0.4 (−0.1)	0.7–4.6 (2.4)

geomorphologists and sedimentologists widely accept an exponential downstream decline of average grainsize in alluvial channels. Several studies (Parker, 1991; Paola et al., 1992; Pizzuto, 1995; Ferguson et al., 1996) have demonstrated the exponential downstream decrease in grainsize in modern and ancient river system.

Downstream variation and controls of the mean grainsize of the bedload sediments can be studied in two ways: (i) the GRV-I and IIA segments as the Himalayan river without influence of major tributaries and (ii) the entire Ganga River as the foreland basin river with prominent influence of tributaries contributing water and sediments inputs from the Himalaya orogenic belt, along with the northern Indian craton and Ganga alluvial plain regions.

The Himalayan river: The 370-km-long upper part of the GRV segment (GRV-I and GRV-IIA) drains a 23,051-km^2 area in the Himalaya orogenic belt region characterised by a steep gradient and high sediment yield. In this zone, the Ganga River enters into the GRV-1 at Haridwar and represents a braided channel pattern with no interference of a major tributary contribution into the main channel (Fig. 4C). This part of the river carries exclusively the Himalaya-derived sediment load distinguished by a wide range of grainsizes (Fig. 4D). Under the present hydrogeological conditions, the Ganga River transports very coarse sand up to 125 km downstream from the base of the Himalaya at Haridwar. Near Hastinapur (G7), the rounded pebbles and gravels (cm size) are found at a depth of 11–12 m below the present-day active channel of the Ganga River (Das Gupta, 1975) and may represent the earlier humid phase of the Ganga, in which these gravels were transported 100 km farther downstream than the present day. Mean grainsize of the megafan sediments present in the GRV-I margins is also relatively coarser than the present-day Ganga River sediments (Shukla et al., 2001). This reveals that, in its recent past, the Ganga River experienced a much higher discharge and sediment budget than the present.

The downstream decrease of gravel content in the bedload sediments can be attributed to a downstream decrease in stream power. Paola et al. (1992) demonstrated that grainsize, water discharge, sediment feed rate and subsidence rate affect depositional sequences in a foreland basin. Fig. 13 displays the linear relations among particle size shown for percentiles D_5 (size of which 5% is finer), D_{16}, D_{25}, D_{50} (median size), D_{75}, D_{84}, D_{95}, and D_m (mean grainsize) on a Φ scale and downstream distance plotted on a linear scale. It provides relatively low downstream fining coefficient ranges from 0.0020 to 0.0045 Φ/km. A downstream change of D_{50} is quite similar to that of D_{mean}. Within a distance of 500 km, D_{50} decreases from 1.00 Φ to 2.00 Φ, and D_{95} decreases from 2.00 Φ to 3.00 Φ. The rates of grainsize reduction are relatively much lower than those reported from gravel bed rivers. Downstream decline in mean grainsize of the bedload sediments in the upper Ganga River can be expressed in linear form as: Mean grainsize (in Φ) = 0.0024 × Distance (in kilometres from mountain front) + 1.29.

The foreland basin river: Mean grainsize of the bedload and suspended load sediments ranges between 1.5 and 3.7 Φ (medium to very fine sand) with an average value of 2.55 Φ and between 2.9 and 5.0 Φ (fine sand to coarse silt) with an average value of 3.9 Φ, respectively. This range indicates that the bedload sediments of the Ganga River are coarser than the suspended load

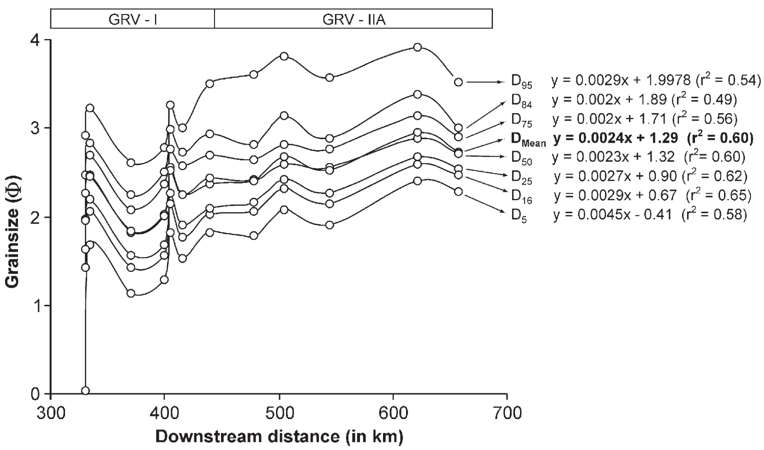

Fig. 13. Downstream variation of D_5, D_{16}, D_{25}, D_{50}, D_{mean}, D_{75}, D_{84}, and D_{95} in bedload sediments of the upper Ganga River (GRV-I and IIA) showing low fining coefficients with moderate to high coefficient of determination.

sediments by 1.5 Φ units. The maximum grainsize value of the bedload sediments is recorded at G1 where the river enters into the Ganga alluvial plain from the Himalaya, and the minimum grainsize value is recorded at G54, where the river enters into the delta region.

Fig. 14 illustrates the relationship between mean grainsize of the Ganga River bedload and suspended load sediments with the downstream distance. The 1800-km-long downstream profile of mean grainsize of the Ganga River sediments shows a linear decline in Φ scale with strong peaked fluctuations. This longitudinal fluctuations in grainsize of the Ganga River sediments is accompanied by downstream increase in the water discharge and by downstream variation in channel slope. This can be explained by (i) the influx of very fine sand-rich sediments originating from the Ganga alluvial plain and medium-sand-rich sediments originating from the northern Indian craton region; and (ii) selective erosion of medium-grained sediments from the river bed. The downstream decline in the size of bedload sediments of the Ganga River can be expressed by a formula presented in linear form as: Mean grainsize (in Φ) = 0.002 × Distance (in kilometres from mountain front) + 3.7.

The GRV-III segment is characterised by an increase in the channel slope along with discharge contributed from the Yamuna River (Figs. 8 and 9B). It also displays a significant downstream increase in mean grainsize within the range of values from 3.28 to 1.50 Φ, from Jahanabad (G26) to Vindhyachal (G33). Downstream coarsening of the bedload sediments refers to a selective erosion (winnowing activity) of finer sediments that leaves coarser fractions of the bedload sediments on the river bed. This coarse bedload material is available from the perennial and several ephemeral tributaries originating from the northern Indian craton region. The Tons River, a perennial river, supplies coarse-grained sediments for the same (Figs. 6A and 11). Laronne and Reid (1993) argued that ephemeral rivers are about 400 times more efficient in transporting coarse-grained sediments than perennial rivers.

Fig. 15 depicts the relationship of mean grainsize of the bedload and suspended load sediments of the Ganga River with sediment fractions. In the bedload sediments, mean grainsize is inversely (r^2 = 0.64) and positively (r^2 = 0.69) related to the dominance of medium sand and very fine sand fractions, respectively. Mean grainsize of the suspended load sediments is positively (r^2 = 0.69) related to the dominance of sediment fraction finer than medium silt and is inversely (r^2 = 0.63) related to the fine–very fine sand fraction. Along with the known rate of the downstream decrease in grainsize of the Himalayan river's sediments, these relationships can be useful in palaeogeographical reconstruction of fluvial sand bodies of the Siwalik and the Ganga alluvial plain sedimentary sequences.

Datta and Subramanian (1997) reported grainsize characteristics of river sediments in the Ganga–Brahmaputra delta region. Mean grainsize of the bedload sediments of the Brahmaputra River (upstream of the Ganga River confluence) is 3.9 Φ (very fine sand), the same as of the Ganga River. Downstream of the Ganga and Brahmaputra confluence, the mean grainsize of the

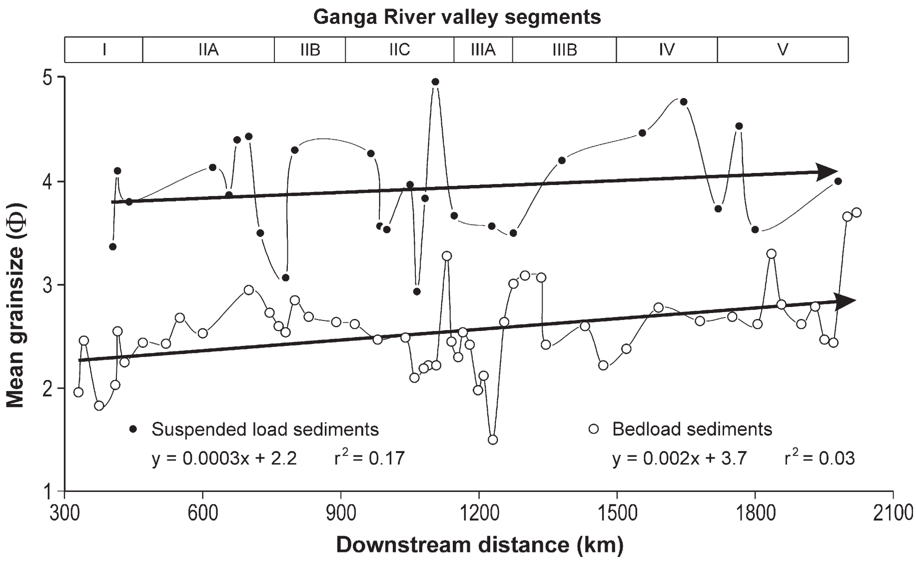

Fig. 14. Downstream variation of mean grainsize of bedload sediments (n = 53) and suspended load sediments (n = 27) of the Ganga River. Note the peaked fluctuation in mean grainsize of the bedload and suspended load sediments.

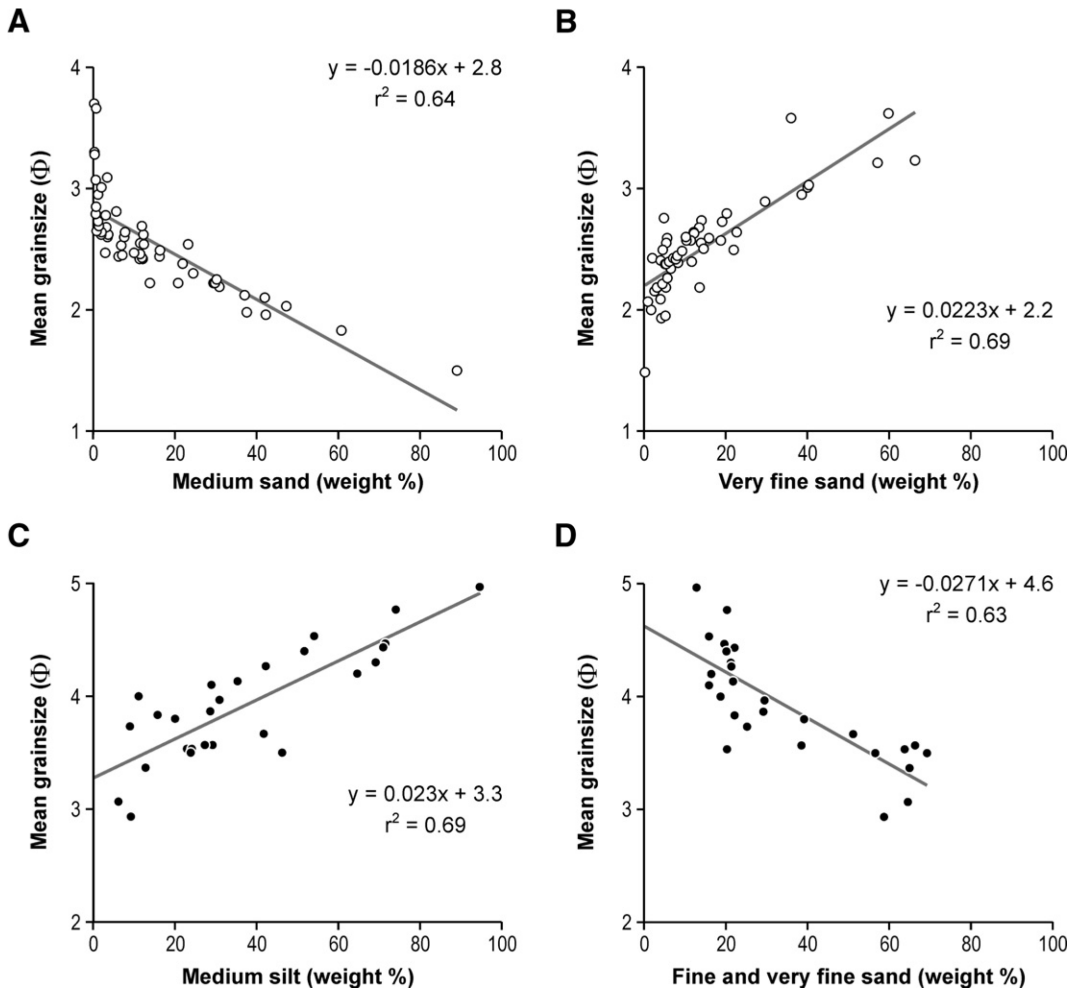

Fig. 15. Scatter plots showing the relationship between (A) medium sand and (B) very fine sand versus mean grainsize of bedload sediments; (C) medium silt and (D) fine and very fine sand versus mean grainsize of suspended load sediments of the Ganga River.

bedload sediments of the Padma River decreases to 4.9 Φ (very coarse silt).

5.1.2.2. Standard deviation, skewness and kurtosis. Standard deviation of river sediments is controlled by four major factors: (i) the grainsize distribution of the source sediment; (ii) the preferential fluvial entrainment of particles for saltation; (iii) effects of gravity by down slope sediment transportation; and (iv) water flow characteristics. The importance and effect of each control vary temporally and spatially. Sorting of the bedload sediments as measured by standard deviation ranges from 0.3 Φ (very well-sorted) to 0.7 Φ (moderately well-sorted). In the suspended load sediments, values of sorting range between 0.6 and 1.6 Φ, with an average value of 1.1 Φ (moderately sorted).

A wide range of skewness and kurtosis values were obtained for the Ganga River sediments. Skewness of the bedload and suspended load sediments ranges between 0.3 and 0.7 (fine to strongly fine skewed) and between −0.6 and 0.4 (fine to very coarse skewed), respectively. Kurtosis values vary from 0.8 to 2.4, indicating a mesokurtic to very leptokurtic distribution in the bedload sediments, and from 0.7 to 4.7, indicating a platykurtic to very leptokurtic distribution in the suspended load sediments.

Fig. 16 demonstrates the downstream variation of standard deviation, skewness, and kurtosis in the bedload and the suspended load sediments of the Ganga River. Overall downstream variations in the grainsize parameters are attributed to fluctuating energy conditions required for the transportation and deposition of the Ganga River sediments in the different GRV (IIB, IIIA, IIIB, and IV) segments. The only major systematic change in the above parameters appears to be in the delta region.

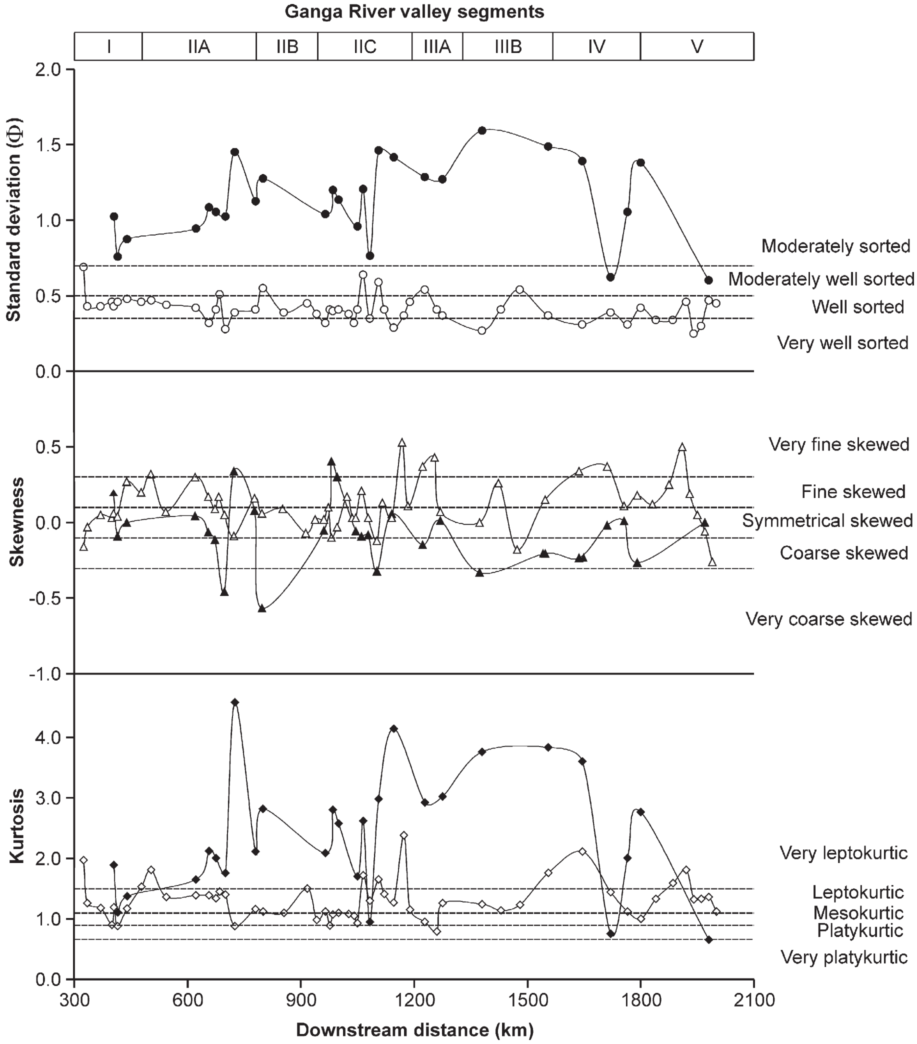

Fig. 16. Downstream longitudinal variations of grainsize statistical parameters (standard deviation, skewness, and kurtosis) of bedload (open symbols; $n=53$) and suspended load sediments (closed symbols; $n=27$) of the Ganga River.

Scatter plots in Fig. 17 show the bivariate relationship of standard deviation, skewness, and kurtosis with mean grainsize of bedload and suspended load sediments of the Ganga River, respectively. Sorting values vary systematically with the mean grainsize in the bedload and the suspended load sediments. The plot of skewness versus standard deviation for the bedload and the suspended load sediments tends to group in two different areas with only a few samples in between (Fig. 18). Folk and Ward (1957) showed that a mixing of sediments from two modes resulted in an elliptic or near circular trend in skewness versus a standard deviation diagram. Moderately sorted suspended load sediments and well-sorted bedload sediments showed symmetry of positively and negatively skewed distributions, respectively. It can be successfully used to discriminate sedimentary environments of modern tropical fluvial systems.

5.1.2.3. Confluence controls on grainsize parameters. The GRV-IV segment has a unique geomorphological setting where the Himalaya orogenic belt tributaries (the Ghaghara and the Gandak Rivers) and the northern Indian craton tributary (the Son River) have a common confluence with the Ganga River (Fig. 6C). These tributary rivers transport their sediment load with distinct textural characteristics (as shown in Fig. 11) and provide an opportunity to understand the confluence control on sediment characteristics of the Ganga River. Table 7 summarizes the changes in characteristics of the bedload and suspended load sediments of the Ganga River before and after the confluence. These changes include a

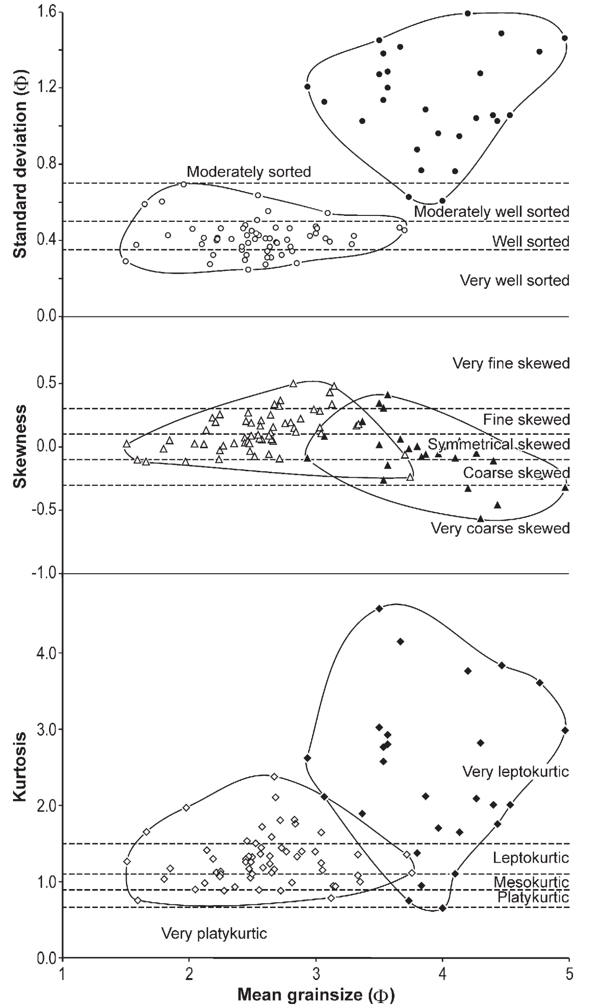

Fig. 17. Bivariate plots of mean grainsize versus standard deviation, skewness, and kurtosis in bedload sediments ($n=53$, open symbols) and suspended load sediments ($n=27$, closed symbols) of the Ganga River.

decrease in mean grainsize and, improvement in sorting, skewness, and kurtosis. These changes are more pronounced in the bedload sediments than in the suspended load sediments. The drastic decrease in medium sand and significant increase in fine sand content of the bedload sediments and medium silt clay content of the suspended load sediments are prominent as textural changes. They are also governed by changes in the channel morphology from meandering to braided and in hydraulic regime due to sediment–water inputs of these tributary rivers.

5.1.3. Cumulative curves

Grainsize distribution of the bedload and suspended load sediments can be related to sediment transportation,

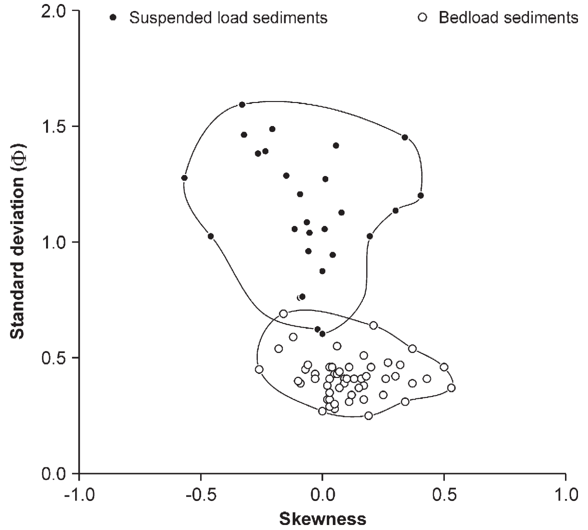

Fig. 18. Bivariate plot of skewness versus standard deviation in the bedload and suspended load sediments of the Ganga River.

usually occurring during high flood discharges. Sediments <3 Φ would normally be transported entirely in suspension without any bedload phase, and these sediments are deposited at low flow stages. A significant part of the explanation for differences in transport behaviour of bedload and suspended load sediments lies in

Table 7
Changes in textural and grainsize characteristics of bedload and suspended load sediments of the Ganga River by the confluence dynamics with the Son, the Gandak, and the Ghaghara Rivers

Sediments	Before confluence	After confluence
Bedload sediments	Dighwara (G42)	Barh (G43)
Textural characteristics		
Medium sand (%)	22	1
Fine sand (%)	69	87
Very fine sand (%)	7	10
Silt and clay (%)	2	2
Grainsize characteristics		
Mean grainsize (in Φ)	2.38	2.65
Sorting (in Φ)	0.54	0.31
Skewness	−0.18	0.34
Kurtosis	1.23	2.11
Suspended load sediments	Buxar (G40)	Barh (G43)
Textural characteristics		
Coarser than fine sand (%)	11	5
Fine and very fine sand (%)	12	15
Coarse silt (in %)	28	26
Medium silt to clay (%)	49	54
Grainsize characteristics		
Mean grainsize (in Φ)	4.20	4.47
Sorting (in Φ)	1.59	1.49
Skewness	−0.33	−0.21
Kurtosis	3.67	3.84

their cumulative curves. As sediments can be transported by river water in various ways, these curves can give an indication of the mechanism and hydraulic conditions under which these river sediments were transported in monsoon-controlled river hydrology. The major grainsize characteristics of sediments deposited in a river bed can undoubtedly be related to bedload transportation during deposition, usually occurring during a fairly narrow range of high flows in flood discharges. Among sedimentologists and hydrologists, it is widely accepted that (in case of unidirection flow) bedload, saltation, and suspension are the three transportation mechanisms of sediments.

The cumulative grainsize curves from both the bedload and the suspended load sediments of the Ganga River are shown in Fig. 19. Data are presented as cumulative curves. Interpretation of shapes of cumulative grainsize distribution curves plotted on logarithmic probability paper appears to be a potentially fruitful approach for our understanding of sediment transportation mechanisms. In the Ganga River sediments, the coarsest part of the cumulative curve shows overlapping distributions indicating that nearly 20% of the bedload sediments move as bedload and the rest (~ 80%) move in suspension. All cumulative grainsize curves of the bedload sediments, therefore, show a distinct "break" in slope, which represents the maximum grainsize transportable in suspension when shear stress attains its maximum values.

5.2. Transportation dynamics

The knowledge of grainsize characteristics of fluvial sediments serves as a basis for a better understanding of its transport dynamics. The manner and nature of sediment transport in a river is of extreme importance to the textural composition of sediments. The knowledge of physical characteristics of the Ganga River sediments along with channel hydraulics, grainsize image, bedform mechanics, and suspension dynamics may help in the understanding of sediment transportation process of the monsoon-controlled fluvial systems.

5.2.1. Channel hydraulics

Pandey (1980) provided base data on detailed hydrological characteristics of the Ganga River at the Mokama (G44) gauging station for the period of August 1958 to August 1959. Daily discharge records are presented in Table 8.

The Ganga River flow regimes can be characterised into four distinct stages: rising stage, flood stage, falling stage, and low stage. In the rising stage, the river

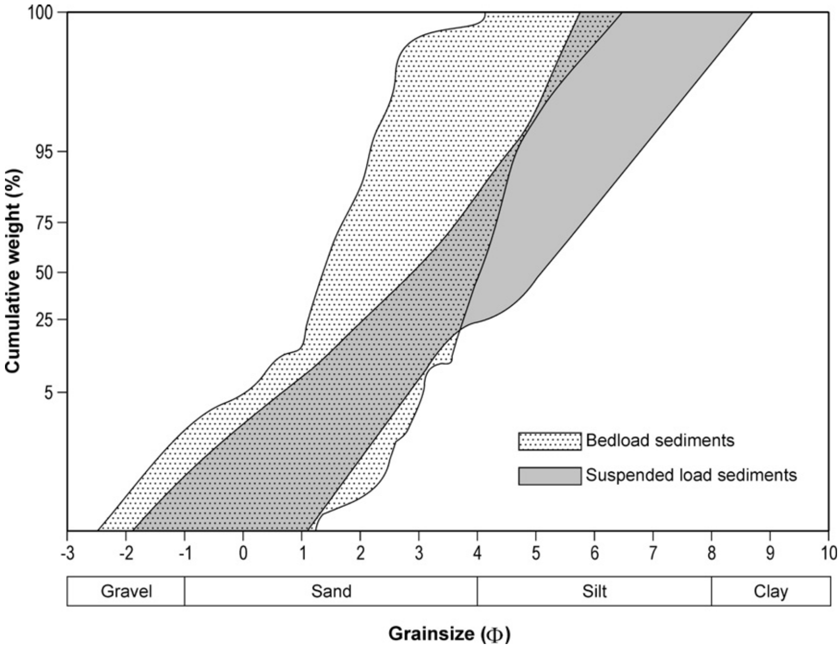

Fig. 19. Comparisons of variability in cumulative frequency distribution curves of the bedload sediments (n = 159) and the suspended load sediments (n = 27) of the Ganga River. Interestingly the suspended load and bedload sediments have a common mode of fluvial transportation. Nearly 80% of bedload sediments are being truly moved as "graded suspension" during the monsoon season by the Ganga River.

Table 8
Hydrological characteristics of the Ganga River at Mokama in 1958–1959 (after Pandey, 1980)

Date of observation	Discharge (m^3/s)	Water level (m)	Maximum surface velocity (m/s)	Mean velocity (m/s)	Water depth mid-channel (m)	Lacey's depth (m)	Flow regime
30.08.58	35,827	41.22	3.96	2.31	14.32	14.93	Flood stage
17.09.58	34,205	41.08	3.89	2.04	18.59	14.63	
29.09.58	20,360	39.76	2.32	1.51	17.06	12.19	
15.10.58	28,571	40.60	3.64	1.95	18.59	13.71	Falling stage
30.10.58	10,345	38.19	1.77	0.93	17.67	9.75	
29.11.58	4360	36.30	1.13	0.55	15.24	7.31	
31.12.58	2914	35.34	0.79	0.43	15.24	6.40	
30.01.59	2488	35.17	0.72	0.41	13.71	6.09	
28.02.59	2325	34.96	0.66	0.39	14.02	6.09	
31.03.59	1844	34.50	0.64	0.37	12.19	5.48	Low stage
29.04.59	1515	34.18	0.55	0.33	11.58	5.18	
02.06.59	1800	34.38	0.56	0.34	11.58	5.48	
01.07.59	3606	35.64	1.80	0.66	11.27	7.01	
14.07.59	10,730	38.05	3.26	1.36	13.71	10.06	
30.07.59	19,586	39.67	3.84	2.11	12.80	12.19	Rising stage
13.08.59	41,114	41.54	4.18	2.93	14.93	15.54	
17.08.59	47,918	42.00	4.15	3.07	14.32	16.46	Flood stage
30.08.59	25,170	40.17	3.17	1.92	12.80	13.10	

channel accommodates an increased volume of water (3600–41,100 m^3/s) during the monsoon by the deepening of the active channel. Water velocity increases from 0.66 to 2.93 m/s. Sediment transportation capacity of the channel exceeds the sediment supply, such that the channel attempts to scour the riverbed to accommodate an increased volume of the monsoon discharge during this phase. At this stage, parameters of peak flood hydraulics are highly variable (Table 5). The rising stage is followed by the flood stage in which high flows take place in a comparatively straight channel. Within a few days, the discharge can increase from 25,000 to >45,000 m^3/s (Table 8). The river water surface displays turbulent cells arranged in a very definite pattern as boils and eddies. Maximum rate of sediment discharge takes place during this stage. Nearly 50% of the total annual discharge flows within a week or 10 d duration (Fig. 9C). Under such dynamic conditions, the bedload sediment transportation causes either partial or complete erosion of sand bars and islands, which were formed in the earlier monsoon cycle. Lateral migration of the active channel is also a prominent fluvial activity at this stage.

In the falling stage, both the river water velocities as well as its turbulence decrease and the flows become less turbulent in character. Aggradation of channel is forced by reduced sediment transportation capacity and decrease in discharge. Maximum amount of deposition of bedload sediments, within the active river channel takes place as water velocity diminishes (Fig. 5B). This generally occurs just before or during the falling stage. As the water level drops, low-stage flow is established in the river channel. In the later part of this stage, the river channel flows over its own riverbed and about a 2−5-m-thick sequence of bedload sediment deposits is formed (Fig. 5C). The river moves as a single sinuous channel, generally bordered by freshly deposited sandbars (Fig. 7A).

During non-monsoon times of the Ganga River, water diversion as the Upper Ganga Canal and the Lower Ganga Canal in GRV-I, lift canals in GRV-IIIA, and sand mining of the active channel bed are the common anthropogenic activities. The bedload sediments of the Ganga River are an important mineral resource used as construction material and considered vital to the economic growth in the Ganga alluvial plain region. Geomorphological representations of these anthropogenic responses are an important field of future studies.

5.2.2. Flow and sediment rating curves

Sediment transportation in the Ganga River can be described by flow and sediment rating curves indicating stage versus water discharge and sediment discharge versus water discharge relationships, respectively. Daily discharge records for the period of 1958–1959 at Mokama are used to construct these curves (Pandey, 1980).

Fig. 20A displays the flow rating curve showing the relationship between increasing stage and discharge in the Ganga River at Mokama (G44). The maximum discharge of 47,918 m^3/s is reached at the maximum flow height of 42 m. Stage–discharge rating curve of the Ganga River displays the logarithmic type of regression in nature with good correlation ($r^2=0.99$).

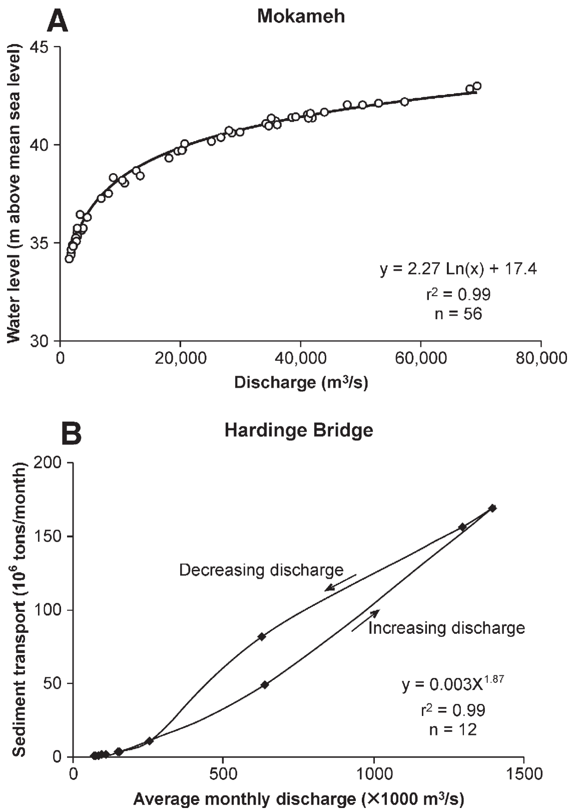

Fig. 20. (A) Flow rating curve showing logarithmic relationship between increasing stage and discharges of the Ganga River at Mokameh station (data source: Pandey, 1980), and (B) sediment rating curve showing the power regression relationship between sediment transport and discharge of the Ganga River at the Hardinge Bridge monitoring station (data source: Coleman, 1969).

Several models were used to relate the rates of sediment transport to flow. The power function ($Y = 0.003X^{1.87}$; where X is discharge and Y is rate of sediment transport) provides a good first approximation. A counter clock loop is observed for the sediment–discharge relationship in the Ganga River at Hardinge Bridge as displayed in Fig. 20B. The curve indicates a higher discharge in the rising limb than the falling limb of a flood wave. A larger shear stress on the rising limb is observed than on the falling limb. The bedload sediment transport also increases with bed shear stress, thus resulting in higher sediment transport during the rising limb than the falling limb at a given discharge.

5.2.3. Grainsize images

Grainsize images are also useful in the interpretation of sediment transport dynamics and are represented by the *CM* and *FM* diagrams. The *CM* diagram is formed by plotting the value of *C*, one-percentile proportional to the median diameter (*M*) value of grainsize distribution at logarithmic scales. Fig. 21A displays a *CM* pattern of the bedload and suspended load sediments of the Ganga River. Most of the points of bedload sediments lie parallel to the $C = M$ line, indicating that *C* is proportional to *M*. This relationship of *C* and *M* is due to the effect of river sediment sorting by bottom turbulence. The good correlation between *C* and *M* shows control of deposition by bottom turbulence. It also indicates that at a given moment, bottom turbulence is competent to support the coarsest particles of bedload sediment under suspension (Passega, 1977).

Just above the river bed, bedload sediments are lifted by bottom turbulence and form a suspension characterised by regular upward decrease in their concentration. This suspension is called “graded suspension” (Passega, 1964). This is the coarsest fraction of suspended load deposits. Grainsize grading is controlled

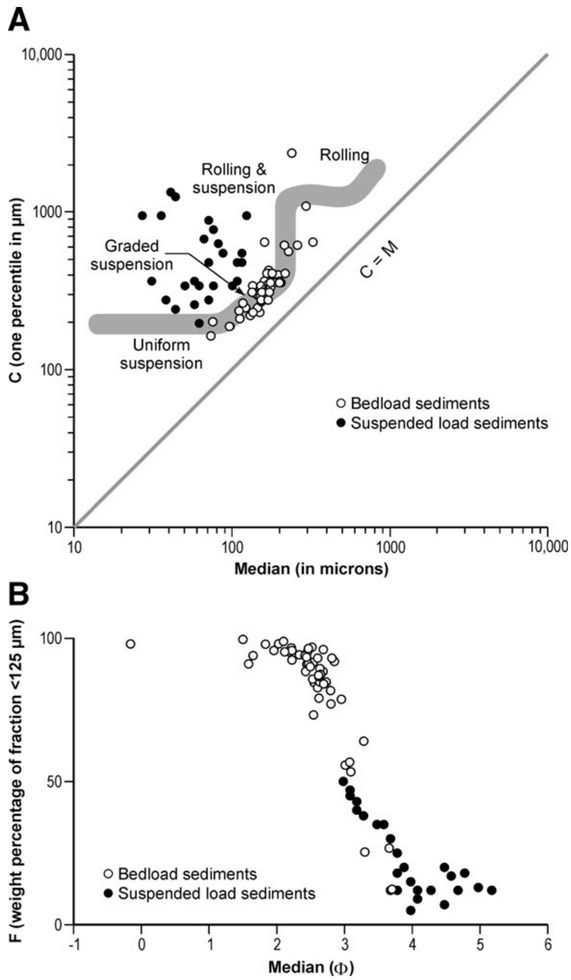

Fig. 21. Grainsize images of the Ganga River. (A) *CM* diagram and (B) *FM* diagram of bedload and suspended load sediments. Most of the bedload sediments are being transported under “graded suspension”.

by turbulence from bottom friction and that the stronger the turbulence the coarser the suspended particles. Bedload sediments in the active channel of the Ganga River are transported by bottom turbulence during the monsoon season. These bedload sediments present an example of graded suspension deposits, which are mostly formed by the coarsest fraction of suspended sediments during transportation. Passega and Byramjee (1969) suggested that an M=100 μm line acts as a dividing line between graded and uniform suspension. Sediments under uniform suspension are generally finer than 250 μm.

In the Ganga River, a graded suspension during the monsoon flow transports the bedload as well as the suspended load sediments. In the Mississippi River, the uniform suspension is always present, while a graded suspension may be lacking. When both types of suspensions are present, the minimum size in the upper part of the graded suspension is the maximum grainsize of the uniform suspension. At Mayersville, the graded suspension is almost 3 m thick at the base of a 20-m-thick suspension in the Mississippi River (Passega, 1964). The *CM* plots of the bedload sediments of the Gomati River, an alluvial river of the Ganga alluvial plain, fall around in both graded and uniform suspensions (Kumar and Singh, 1978). In the *FM* diagram, *F* indicates the percentage of fractions finer than 125 μm. Fig. 21B shows the *FM* diagram of the Ganga River sediments that can be easily distinguished by the bedload sediments that show less scatter as compared to the suspended load sediments.

5.2.4. Channel bedform sequence

The erosional and depositional processes of channelized flow depend upon the interaction between turbulent flow, sediment transport, and bedforms (Leeder, 1983). Bedforms provide a valuable check on hydrological reconstructions and sediment transportation (Allen and Leeder, 1980). Knowledge of the changes in bedform dimensions during varying flow conditions is very limited. The Ganga River shows changes in bedform dimensions after every monsoon season (Fig. 5C, D).

Fig. 22A presents the longitudinal section of an 80-m-long and 3-m-high braid bar complex exposed above the water level during the summer at Bithur (G18). The bar is made of positively skewed, leptokurtic, well-sorted, very fine sand. The section exhibits well-developed, three (A, B, and C), vertically stacked, lensoid-shaped bar sequences that are separated by erosional

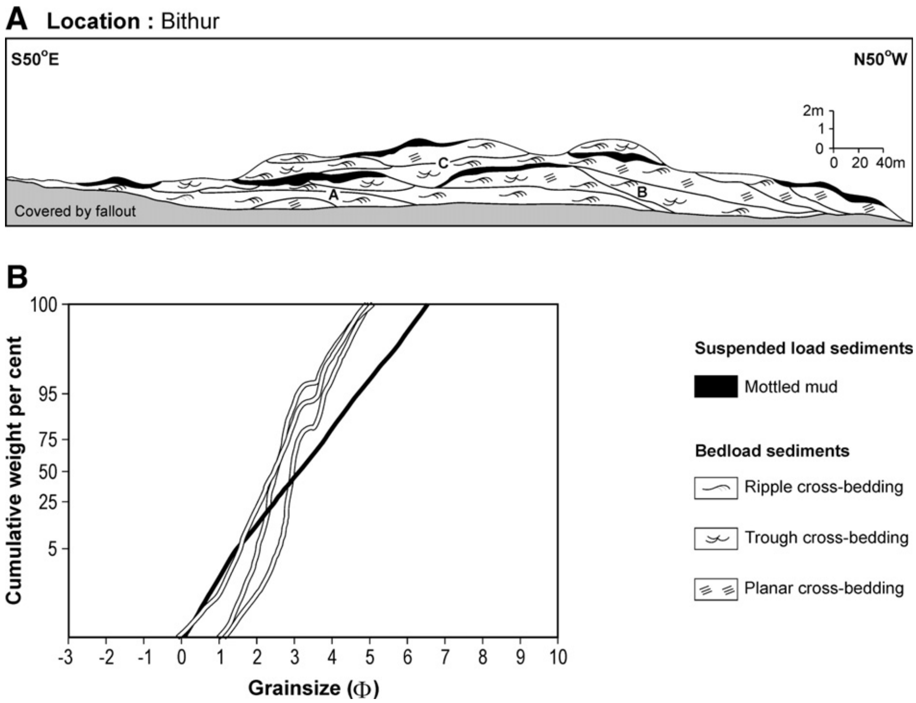

Fig. 22. (A) Longitudinal section of a braid bar complex of the Ganga River near Bithur showing three bar depositional events (A, B, and C). These events are separated by erosional contacts, mottled, deformed mud horizons, and are produced during high magnitude floods (modified after Shukla and Singh, 2004). The bedload sediment-laden water overtops during the flow of peak monsoon discharge. Location of Bithur is shown in Fig 10. (B) Frequency distribution curves of three bedload and one suspended load sediments collected from the Ganga River at Bithur.

surfaces with distinctive lithofacies associations. The bar exhibits a distinctive fining up sequence of low-angle cross bedding, planar-and-trough cross bedding, ripple bedding, and parallel lamination developed in sand and overlain by mottled mud (Shukla and Singh, 2004). Sometimes, these bar sequences may also be separated by a lensoid, deformed silty mud horizon, if the successive flood events are of low magnitude. During high intensity flood events, development of a cross-bar channel over the bar may take place, which deposits a new bar sequence over the existing bar.

Sedimentary stratifications of the braid bar indicate the grainsize distributions of the bedload and the suspended load sediment transported and deposited by turbulent monsoon flows. Fig. 22B displays the frequency distribution of bedload and suspended load sediments as 5−25% of bedload that are transported as intermittently suspended load. During monsoon flow, the upward directed turbulence causes bedload sediments to be moved downstream in suspension for some time. Observed bedload sediment distribution in the exposed part of the bar sequence is associated with a distinct transportational and depositional event.

5.2.5. Sediment transportation process

Depositional and erosional processes of a river depend upon the interaction between channel flow, sediment transport, and bedforms (Leeder, 1983). In alluvial channels, flow regime has significant effects on channel morphology and sediment load transportation. Duration

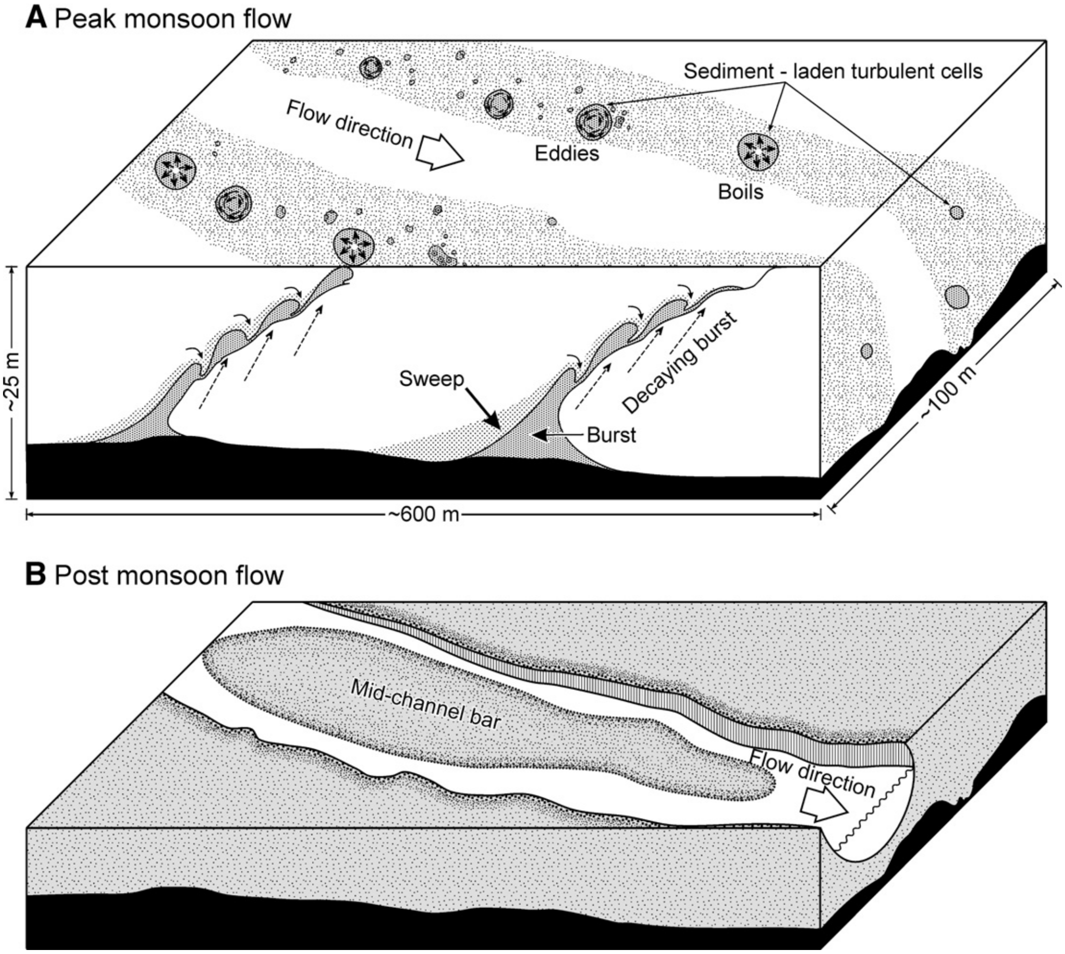

Fig. 23. (A) Schematic presentation of a three-dimensional view of the turbulence pattern in the Ganga River water, developed and seen in the active channel during the flow of peak monsoon discharge. High-speed turbulent ejections with bedload sediments move up and downstream from the riverbed (based on Leeder, 1983). Sediment-laden turbid river water (with turbulent cell patterns: boils and eddies) forms the elongated rows parallel to flow direction in the middle of active channel. Darker shading indicates heavier sediment concentrations. (B) The active channel morphology of the Ganga River after monsoon season. Drastic decrease of the water discharge during the falling stage causes aggradation of the active channel bed by deposition of a 5- to 10-m-thick sequence of bedload sediments. The active river occupies a narrow channel through the sandbars.

and intensity of monsoon discharge controls the sediment transportation dynamics of the Ganga River. Bridge (1981) opined that grainsize distributions of bedload sediment transported and deposited by unidirectional flows are very strongly influenced by turbulent flow. Leeder (1983) observed turbulent flow structure during alluvial sediment transportation and characterised transportation process as burst–sweep cycle. From the rivers of the Indian subcontinent, Coleman (1969) studied the turbulence pattern of the Brahmaputra River in detail.

A three-dimensional model for sediment transportation dynamics in active channel of the Ganga River during monsoon flow is proposed in which two prominent characteristic flow zones are recognised: peak monsoon flow and post-monsoon flow. The bedload sediments rising from near active channel bottom occurred within lifted fluid of a burst event. Fall of sediments encouraged by high speed fluid sweeps that penetrate to the bottom, spread out sideways, and deliver sediments into an adjacent low-velocity zone of the active river channel. The burst–sweep cycle accommodates a high amount of fluvial energy available within the monsoon flow of river. Bagnold's concept of anisotropic turbulence explains turbulence as upward moving burst and slow downward moving sweep on the riverbed (Leeder, 1983). Surface turbulence cell patterns (boils and eddies) randomly appear at the water surface in the middle of the channel for 10−15 s. Fig. 23A illustrates these cells at the water surface and within the channel. Coleman (1969) describes in detail the nature and characteristics of these cells in the Brahmaputra River. After the monsoon season, the active channel in the Ganga River aggrades because of the reduction in water discharge and in the sediment transportation capacity. Fig. 23B displays the schematic presentation of aggradation in the active channel of the Ganga River after the monsoon season.

6. Conclusions

The Ganga River sediments are a complex mixture of gravel, sand, silt, and clay particles weathered from the northern part of the Indian subcontinent and eroded in response to a complex interaction of the Himalayan foreland basin tectonics and monsoon climate. Understanding the interaction between the river's bedload sediments, suspended load sediments, channel geometry, water flow, sediment transport, and filling of alluvial sedimentary basins will enhance our ability to interpret palaeochannel geometry, hydraulics, and migration in ancient or modern channel systems along with their subsurface geometry and facies in the fluvial depositional sequences of the world. The extremely high rate of water discharges, and huge sediment load during monsoons and the high discharge variability make the Ganga River the world's best natural laboratory for the detailed study of sediment–water interactions and fluvial processes of climate-controlled fluvial systems.

Acknowledgements

This work was financially supported by the Council of Scientific and Industrial Research (CSIR), India, and by Deutscher Akademischer Austausch Dienst (DAAD), Germany, through research grants in the form of fellowships to MS. We express his warm appreciation to Dr. Sita Ram Singh, Sahibganj, and Dr. Ashok K. Singh, SNSRKS College, Saharsa, for providing hospitality during the sampling programme of the present study. Prof. S.K. Singh and Prof. M.P. Singh, Department of Geology, University of Lucknow are thanked for their support and encouragement. We wish to thank Dr. Ratan Kar, Birbal Shani Institute of Palaeobotany, Lucknow, and Ms. Anju Saxena for reading the draft of manuscript. Prof. R.A. Marston, Kansas State University, and two anonymous reviewers are thanked for their helpful comments and suggestions on the manuscript during review. We are thankful to Mr. Pramod Kumar Joshi for making the diagrams.

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