

Chapter 8

River Dynamics of the Ganga and Its Tributaries in the Siwalik-Tarai Region of Haridwar District, Uttarakhand, India



Rupam Kumar Dutta

8.1 Introduction

Himalayan rivers occupy a highly dynamic environment with extreme variability in discharge and sediment load. Therefore, shifting of river courses and scouring of bed and banks are some of the most distinguishing characteristics of the Himalayan rivers (Kale, 2002). Except the Siwalik ridge, the entire study area of Haridwar district falls under the geomorphic region of Ganga alluvial plain. Several scientists have contributed their extraordinary works on the geological and geomorphological significance of the Ganga alluvial plain. Geomorphological characteristics of the region have been vividly discussed by many scientists (Shukla & Bora, 2003). The understanding of geological significance and tectonics of the area is very helpful to study the dynamic natures of the Ganga, and its tributaries have been analyzed by several renowned workers (Srivastava et al., 2003; Uniyal et al., 2010). The dynamic natures of rivers in the Ganga plains have been known to engineers and earth scientists for a long time. The most common types of changes identified in the Ganga plains are shifting in channel position due to avulsion, alternation of the flow direction because of cut-off, and channel widening in response to bank erosion and/or bar development. Apart from geology and tectonics, the geomorphic characteristics of an area play a crucial role in influencing the dynamic nature of the rivers in the study area. Jones and Schumm (1999) have nicely illustrated avulsion classification. Mukhopadhyay (2010) also described the mechanism of channel avulsion in floodplain surface. Most of the scientists (Srivastava et al., 2003) have established the concept of different existing geomorphic surfaces of the Ganga plain including fan surfaces and their development in different geological periods. Different parts of the Ganga valley exhibit various salient geomorphic signatures

R. K. Dutta (✉)

Department of Geography, Kultali Dr. B.R. Ambedkar College (University of Calcutta), Parganas, West Bengal, India

through its channel behavior. Depending on the morphological characteristics, the Ganga valley has been classified into seven segments by some scientists (Singh & Singh, 1992). From the previous study it is found that the Himalayan foothill, over a long time periods channels must shift over its entire surface to maintain fan form (Field, 2001). The diversity in channel morphology is caused due to variability in water discharge, sediment load, ground slope, human activities, and tectonic influences (Valdiya, 2003). River channel dynamics are natural autogenic occurrences for rivers with influences from geological, geomorphological, and climatic factors including human modification. Kumar (1995) has showed long-term changes (1922–2000) of channel widening in all rivers of the Rajaji National Park, Haridwar, in his remarkable works on the sustainability of the park. Dutta (2017) has also analyzed controlling factors of salient changes in Ganga River channel near Haridwar city and its adjacent areas based on intensive field survey.

Several articles and reports by earlier scientists have been consulted to study the trend of research on Ganga River dynamics and find the gap in the research of the earlier works. The present work has uniquely focused on several issues regarding Ganga River channel characteristics of Haridwar, which were hardly discussed in the previous studies. In this chapter, the shifting pattern of the entire Ganga River of the district in more than three decades (1967–2005) has been illustrated. Comprehensive understanding about the shifting pattern is important for proper planning on land use as well as pre-hazard management along the vulnerable zones of riverbanks in significant city, such as Haridwar.

Previous scientists have established the concept of different existing geomorphic surfaces of the vast Ganga plain, but the present chapter specially highlights the four physiographic divisions of the study area to distinguish salient channel characteristics under different physiographic zones. To analyze the role of physiography on channel forms, proper ideas about physiographic divisions of an area are very crucial.

The earlier scientists have mainly focused on major physical factors (geology, tectonics, geomorphology, etc.) in their research, but the present work has not only discussed the physical controlling factors of river channels but also distinctively stated the influence of anthropogenic effects (Upper Ganga Canal and Bhimgoda barrage, channel mining, religious activities) on channel instability.

The objective of the chapter is to study the dynamic natures of the Ganga River and its other major tributaries with special emphasis on diverse fluvio-geometrical parameters (channel width, depth, pattern, area, the number of channel bars, etc.) under different physiographic zones like Siwalik, Bhabar, and Terai of Haridwar district, part of the upper Ganga plain, in more than three decades. The present study has focused on different prime-controlling factors (physical and anthropogenic) of aggrading, widening, shifting, and scouring nature of the present Ganga River channel including different types of channel avulsion and abandonments.

8.2 Materials and Methods

This chapter illustrates river channel dynamics of the Ganga and its tributaries of Haridwar district with modern methods including field techniques.

A broad drainage map of the study area has been prepared with the help of toposheets (SOI, 1967) and satellite images (LISS-III, 1997) to get the idea about drainage pattern of the Ganga and its tributaries in Haridwar.

The shifting trend of Ganga River (1967, 199, and 2005) has been illustrated with the help of toposheets (SOI, 1967) and satellite images (LISS-III, 1997 and 2005) (Table 8.1). IRS LISS-III, 1997 & 2005 and LISS-IV, 2005 have been purchased by the author from the National Remote Sensing Centre (NRSC). The change detection map clearly reveals maximum tendency of channel shifting in Terai zone. Major physical factors (geology, tectonic setup, geomorphic surfaces, variability of water discharge, sedimentation) and anthropogenic factors (Upper Ganga Canal and Bhimgoda barrage, channel mining, religious activities) have been identified and discussed by the author with the help of intensive field documents (field survey from 2006 to 2017) and profiles (1445 m cross-section of the Ganga River, longitudinal profile from Sukhrao valley of extreme north to Ganga River of extreme south) as the causes of shifting and dynamic nature of the Ganga and its tributaries. In order to relate river channel pattern with geological structure and geomorphology of the area, broad geomorphological and geological maps have been prepared by the author with the help of the geological map of Saharanpur (GSI, 1997) and the Survey of India toposheets (no: 53 K/1, 53 K/2, 53 K/5, 53 J/4, 53 G/13, 53 G/14) of the years 1967 and 1971. Physiographic division map of the study area has been prepared to differentiate the variation of channel characteristics in Siwalik, Bhabar, and Terai zones. Few sites have been identified like Nildhara area (near Chandi bridge), Kangri, Tatwala, Gajiwali-Shyampur villages, etc., which investigate channel shifting; bank erosion and avulsion events and their impacts on settlement, depending on field observation; GPS tracking over satellite image (Google Earth, 2016 and 2020) (Table 8.1); and the study of channel cross-section. Time series analysis has been done of Chillawali and Sukh rivers to find out the trend of channel widening from 1922 to 2000. The increasing trend of river channel width has been studied (Table 8.2) to establish the dynamic natures of the tributaries. Average annual increasing rate of channel width in different tributaries (in Siwalik zone) has been calculated by the author to show the channel instability. In order to explain the impacts of sedimentation on channel bars and the aggrading attribute of braided channel (in Bhabar-Terai), the area of a mid-channel bar of Ganga River, near Chandi bridge, has been measured to study its spatiotemporal changes

Table 8.1 Details of satellite data used in the chapter

Satellite sensor/product	Date of image
IRS LISS III	30 November 1997
IRS LISS III	24 November 2005
IRS LISS IV	27 November 2005
Google Earth	March 2016 and May 2020

Table 8.2 Average rate increase of the river width in Rajaji National Park (Kumar, 1995)

River name	Channel width (1922)	Channel width (2000)	Changed width within 78 years	Average annual increasing rate of width of the rivers (meter/year)
Malowali River	62.18	152.4	90.22	1.1567
Beenj River	112.47	215	102.53	1.3145
Sukh River	139.92	309	169.08	2.1677
Andheri River	42.06	314	271.4	3.4795
Gaj River	87.78	342	254.22	3.259
Gholana River	10.97	349.7	338.73	4.3427
Bam River	59.44	374.8	315.36	4.0431
Mohand River	182.88	492	309.12	3.9631
Chillawali River	291.69	590	298.31	3.8245
Betban River	307.24	968.8	661.56	8.4815

(1967–2010). Emphasis has been given on field observation for understanding the impact of flood discharge on river channel morphology (2010, 2013). Besides these, special attention has been provided on anthropogenic interferences with river channel like the construction of Bhimgoda barrage and Upper Ganga Canal based on Wolman's (1967) model. In order to elaborate the discussion, relevant primary and secondary data have been analyzed in different qualitative and quantitative approaches. Depending on the comprehensive study, the author has drawn conclusion emphasizing a few significant findings.

8.2.1 Area and Location

From Haridwar, the Ganga River flows through into the regional surface of the Ganga alluvial plain. Therefore, Haridwar, the study area, falls under part of upper Ganga plain. The Haridwar district consists of three Tahesils, namely, (1) Haridwar, (2) Roorkee, and (3), Laksar, including six blocks, namely, (1) Bhagwanpur, (2) Roorkee, and (3) Narsan, (4) Bahadrabad, (5) Laksar, and (6) Khanpur. The study area extends from 29°35'37"N to 30°13'29"N latitude and 77° 52' 52"E to 78° 21' 57"E longitude, covering an area of 1883 sq km. The main noticeable characteristic of the study area (Fig. 8.1) is its numerous tributaries, (Raos) Malowali, Beenj, Mohand, Sukh, Chillawali, Chikna, Gaj, Andheri, Binj, Dholkhand, Sampuwali, Mallawali, Bam, etc., flowing from northeast to southwest direction according to the slope. The northern portion of the area includes young folded tertiary Himalayan mountain, and the southern part falls under the Ganga-Yamuna

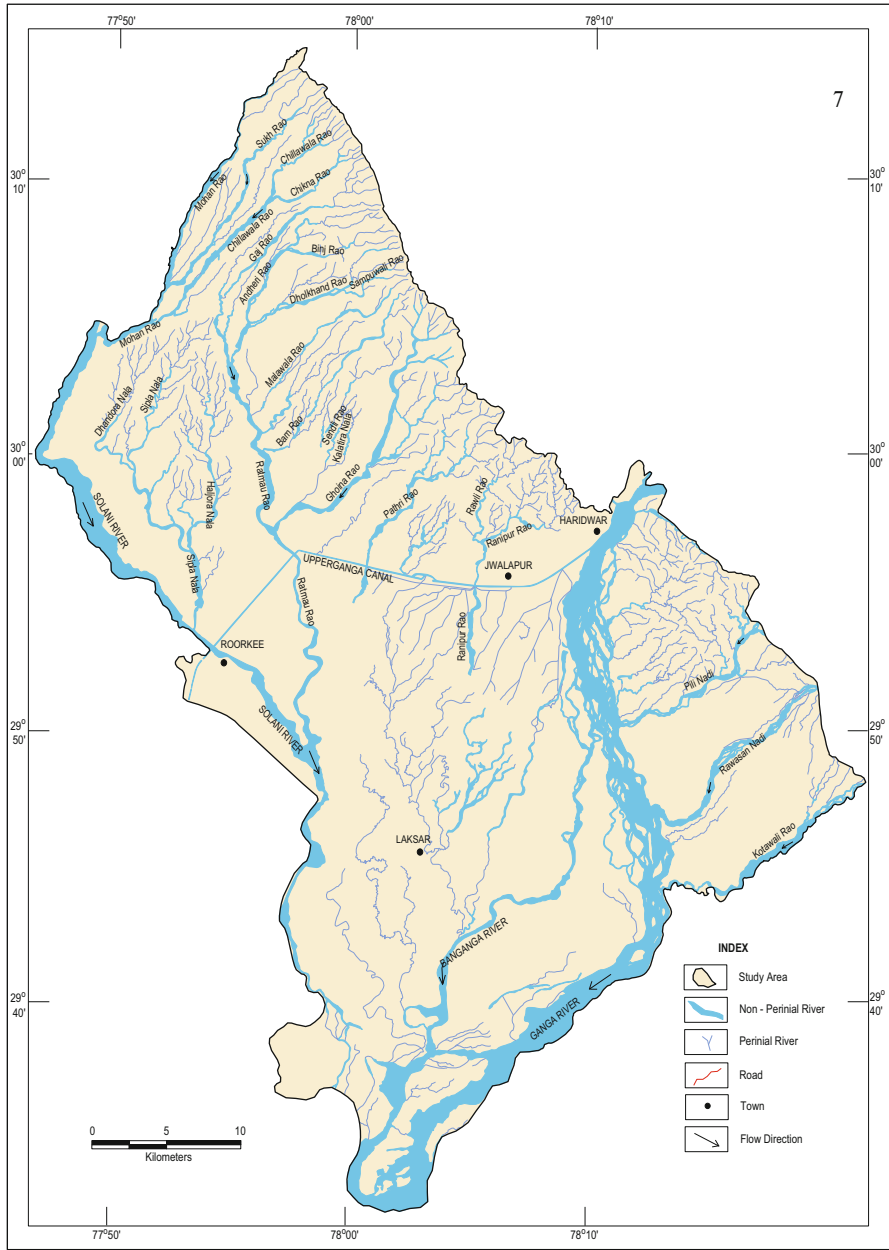


Fig. 8.1 The study area showing broad river network. (Source: Prepared based on toposheets, SOI, 1967)

Doab. In the north-south direction, the study area extends from Siwalik Himalaya to Terai. Along the western boundary of the study area, Solani River flows, and ultimately at the extreme south of the area, it joins with Ganga River. The northern and eastern parts of the area maintains administrative boundary of Haridwar district. The study area consists of enough variation of topographic distinctiveness like upper and lower Siwalik, Bhabar, and Terai plain.

8.2.2 Geological Characteristics of the Study Area

Geological structure is a dominant controlling factor to influence the channel behavior in different physiographic zones (Siwalik, Bhabar, and Terai) of the study area.

The northern part of the study area falls under the outer Himalaya. The outer Himalayan belt consists of the recently uplifted Siwalik of Miocene-Pleistocene detrital sediments, namely, coarse sandstones, clays, and conglomerates.

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 (Singh et al., 2007).

With the help of a geological map (Fig. 8.2) of the Geological Survey of India (1997), the entire study area is categorized with three major geological groups: Siwalik group, older alluvium group, and newer alluvium group. The Siwalik group of the study area belongs to the Pleistocene to Early Pleistocene age. This geological group consists of two geological units: upper Siwalik and middle Siwalik. The upper Siwalik unit is very distinctly noticed in the form of conglomerate, sandstone, and claystone sequence in the study area. The middle Siwalik unit is mainly characterized with gray micaceous sandstone, siltstone with conglomerate lenses. The formation of older alluvium group including two geological units Varanasi alluvium 1 and Varanasi alluvium 2 took place in between the Middle to Late Pleistocene. Brownish silt and sand are the prominent lithological imprints of Varanasi alluvium geological unit. The formation of Varanasi alluvium 2 is the comparatively recent deposits.

The salient features of the newer alluvium formation of the Holocene age is found over the vast area of Haridwar. Three types of newer alluvium formation are identified by the Geological Survey of India. These are channel alluvium, terrace alluvium, and fan alluvium which have been discussed earlier by several scientists (Srivastava et al., 2003). Main lithological units of channel alluvium are micaceous sands, gravel lenses, and silt. Terrace alluvium is mainly characterized with gray sand, silt, clay, and gravel lenses. major portion of the area is covered with gravel, sand, brown silt, and clay as the lithological expression of fan alluvium geological unit. In the extreme northern parts of the study area, due to structural control on river courses, channels are comparatively confined, but as the rivers flow toward the southern direction of the district, river channels become gradually unconfined, and at the extreme south mainly in the Terai zone, the Ganga River channel becomes extended with braiding nature.

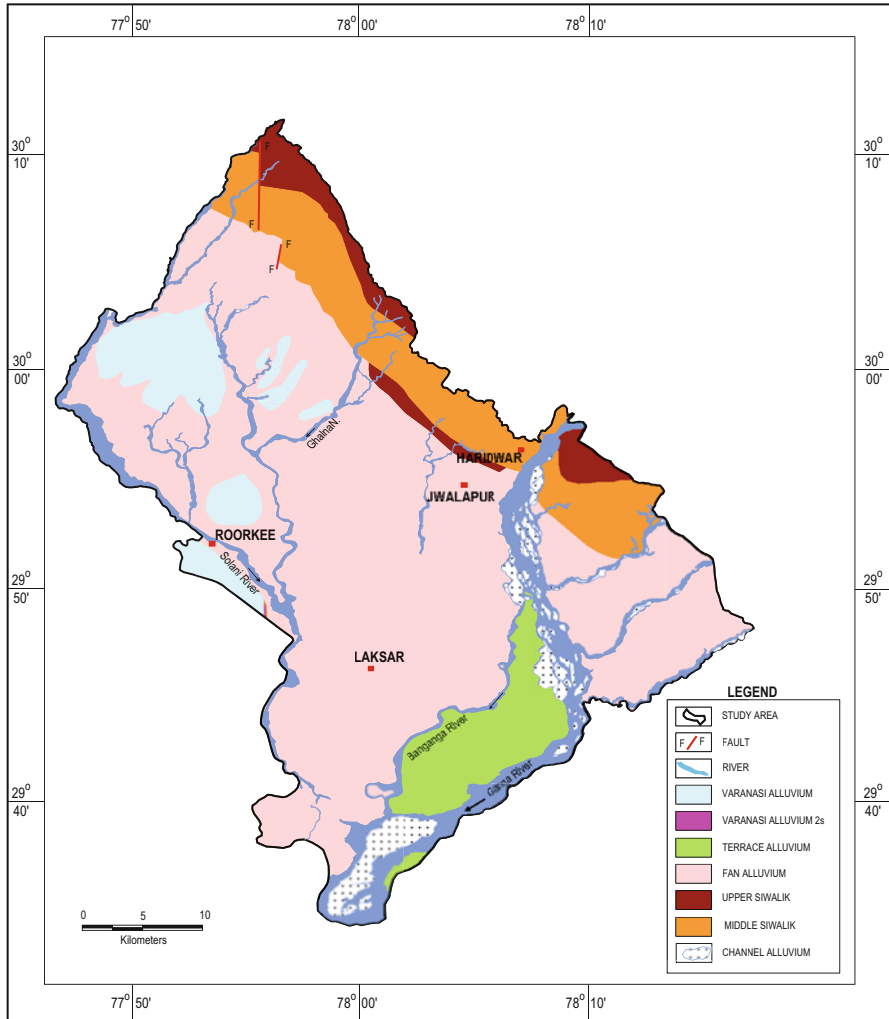


Fig. 8.2 Geological map. (Source: Prepared based on District Resource map of Saharanpur, GSI, 1997)

8.2.3 Tectonic Setup of the Area

The evolution of the Ganga plain foreland basin is related to the collision of the Indian and Asian plates during the early Miocene and the closure of Indus-Suture during the Late Cretaceous. The Ganga basin expanded and attained its present configuration during the Late Quaternary (Singh, 1996a, b).

So, the Ganga plain is an area of compressional stresses and active tectonics. Many of the geomorphic features like the alignment of river channels, distorted

meanders, asymmetrical escarpments, terraces, etc. of the Ganga plain are tectonically controlled (Singh & Rastogi, 1973; Singh, 1996a, b).

The northern portion of the area includes young folded tertiary Himalayan mountain which is tectonically very sensitive due to the presence of several faults and thrusts. In between Mansa and Chandi hill, Ganga Tear Fault (GTF) is situated along the Ganga River valley. Toward north of the Haridwar city, Himalayan Frontal Thrust (HFT) is located along the Siwalik ridge. The HFT has separated the northern Siwalik formation from the southern vast Terai region, which is under the characteristics of fan alluvium. The east-west trending Bhimgoda thrust is present in just the northern part of Haridwar city.

8.2.4 Geomorphological Characteristics of the Area

Different eminent scientists (Srivastava et al., 2003) have identified the major regional geomorphic surfaces in the Ganga plain, like the (1) upland interfluvial surface (T2); (2) marginal plain upland surface (MP); (3) megafan surface (MF); (4) piedmont fan surface (PF); (5) river valley terrace surface (T1); and (6) active flood plain surface (T0). The present author has prominently identified major geomorphic surfaces which have significant role to influence the channel behaviors of the area.

The study area falls under the Ganga-Yamuna megafan (MF). At the foothill of the Siwalik, the Himalaya series of piedmont fan surface (PF) are prominently observed by the author. The Ganga River and its several major tributaries in Haridwar have been characterized with well-marked river valley terrace surface (T1) and active flood plain surface (T0). Channel behaviors of different rivers are greatly controlled under those major geomorphic surfaces.

The Ganga Megafan Surface

Except Siwalik, the entire study area is a part of the Ganga megafan (Fig. 8.2). The megafan surface shows several N-S aligned drainage channels (Shukla et al., 2001). The fan surface is most deeply incised by the active Ganga River and other rivers like Ranipur Rao, Solani, Ratmao Rao, etc. near the Himalayan foothill. Prominent channel scarps of those rivers indicate active incision of channels over the megafan surface. At present, the megafans are relict features, and the surface is being modified by sheet erosion and minor channels as observed by the author near Sureswari temple area, in Ranipur forest range.

River Valley Terrace Surface (T1)

Terraces are the remnants of the earlier riverbed. The major rivers of the Ganga plain display abroad alluvial terrace surface (T1) (Fig. 8.3). In Haridwar the active channel of Ganga and other major rivers have developed paired and unpaired terraces, which

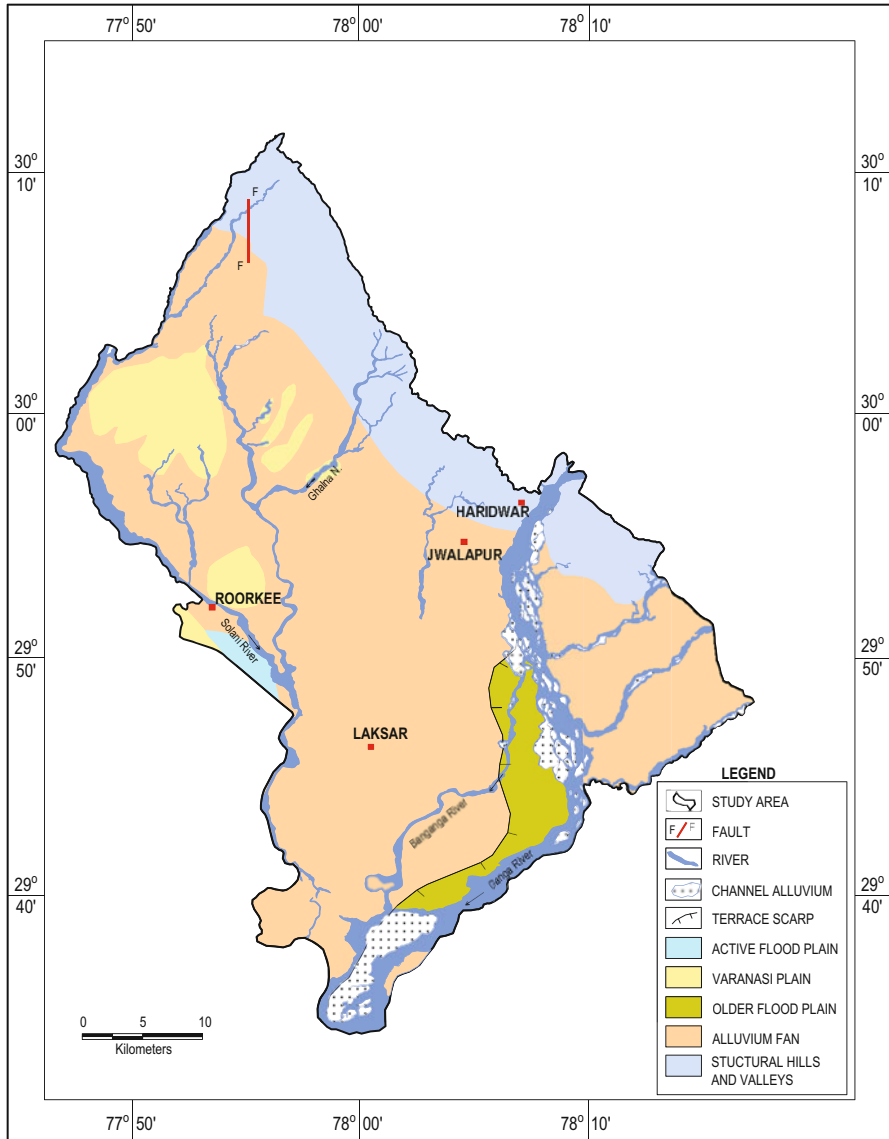


Fig. 8.3 Geomorphological map of the study area showing different geomorphic surfaces (Source: prepared by the author based on DRM, Saharanpur, 1997)

are the evidences of strong incision over the earlier terrace surfaces. Channels over the T1 surface are Yazoo type (Fig. 8.1). The surface exhibits features like abandoned channels and meander cut-off (Singh, 1996b).

Piedmont Fan Surface (PF)

PF is a 10–30-km broad belt formed by coalescing gravely piedmont fans. The PF is superimposed on the MF. Numerous small and braided, parallel to subparallel, ephemeral streams drain the surface. The major rivers, which flow through the surface, are deeply incised. The gravels are subangular to angular and are derived from the Himalaya and from the upper Siwaliks. The surface is mostly covered by silty sediments and is densely vegetated. The PF is cut by ephemeral streams, which carry well-rounded pebbles and possess terrace deposits of rounded pebbles. They are the deposits of the Late Holocene (Singh, 1996b).

Active Flood Plain Surface (T0)

This surface essentially comprises the presently active channel and their flood plains. Due to entrenched nature of most of the rivers, this surface is narrow with small and poorly developed floodplains (Fig. 8.3). The surface is subjected to annual flooding and exhibits a variety of landforms, namely, channels, sandbars, levees, meander cut-off, and swamps. In recent years, the active channel (T0 surface) of many rivers of the Ganga plain shows increase in the area of active sandbars, indicating ongoing aggradations. The author has analyzed a mid-channel bar (Dutta, 2017) which is also increasing its size in the last three decades indicating significant river dynamics. Such an accelerated siltation in the rivers has sometimes been attributed to anthropogenic activities (Singh, 1996a).

On the basis of distinctive assemblages of valley morphology and channel characteristics, the Ganga River valley (GRV) has been divided into seven segments. Out of the seven segments, the study area mainly falls under GRV-I: Haridwar to Garhmuktesar and GRV-0: Gaumukh to Haridwar (Singh & Singh, 1992; Singh, 1996a, b).

At 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. In GRV-I the river valley terrace (T1) 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 (Singh et al., 2007).

8.3 Result and Discussion

8.3.1 Analysis of Channel Characteristics

In Haridwar, the main Ganga River and its several tributaries have developed Yazoo types of drainage pattern (Fig. 8.1) (Uniyal et al., 2010). The present researcher has divided four physiographic divisions depending on major breaks in the longitudinal profile drawn from the extreme north to south of the district (Fig. 8.10) like the (1) higher Siwalik ridge zone, (2) dissected lower Siwalik, (3) Bhabar, and (4) Terai to differentiate the channel characteristics in different physiographic zones.

Altitudinal Variation and River Dynamics

Higher Siwalik Ridge Zone (More Than 500 m)

From 500 meter to 900 meters, the physiographic zone has been considered by the author as higher Siwalik ridge (Fig. 8.7) which is extended along the northern limit of the study area. The main noticeable characteristics of the zone are the numerous tributaries (Raos) Malowali, Beenj, Mohand, Sukh, Chillawali, Chikna, Gaj, Andheri, Binj, Dholkhand, Sampuwali, Mallawali, Betban, Bam, etc. flowing from north-east to south-west direction according to slope along with the major distinct breaks of slope forming narrow gorges (Fig. 8.4). The channel of these rivers in this zone is comparatively steeper and mainly covered with bigger size of boulders. Active fluvial incision is prominently observed along the river channel in the higher Siwalik Himalayan zone of the area.

Dissected Lower Siwalik Zone (300–500m)

In between 300 and 500 meters (Fig. 8.7), the author has identified dissected lower Siwalik zone. In this zone a series of micro-alluvial fans have been developed under the process of fluvial deposition. Earlier scientists (Srivastava et al., 2003; Shukla

Fig. 8.4 Mohand Rao flowing through well-marked gorge in higher Siwalik range near Mohand, along NH-72A. (Source: Field survey, October, 2008)



Fig. 8.5 Deeply incised left bank with wide, flat boulder channel of Mohand Rao in dissected lower Siwalik near NH-72A. Gate no. 2, Mohand, Rajaji National Park, Chillawali Range Mohand. (Source: Field survey, October, 2008)



et al., 1999) had already stated those fans as piedmont fan in their works. The Haridwar city is located at the transitional part of the dissected lower Siwalik and Bhabar zones. As there is an abrupt decrease in the gradient of the slope in topography from higher Siwalik to dissected lower Siwalik, stream velocity suddenly declines and fluvial materials are deposited over the riverbed. So, wide, flat boulder channels (Fig. 8.5) are observed in these zones. Several temporary channel bars are the characteristic features of the rivers. In these physiographic zones, channels are covered with boulders, cobbles, and pebbles. During torrential rainfall of monsoon period, flash floods occur in these channels. So at the junctional point between higher Siwalik and dissected Siwalik zones, the channel widths of all tributaries are suddenly increased. Depending on the data provided by Kumar (1995) (Table 8.2), it has been found that the average annual increasing rate of channel width in different tributaries varies from about 2–9 meter/year. Time series graph shows positive trend of increasing width with time (Fig. 8.13) of Chillawali Rao and Sukh Rao (Fig. 8.13). Apart from this, in this zone, channel aggradation in all rivers is evidently noticed. During flooding condition the channels become unconfined, and active avulsion occurs in the channel courses of the rivers. Continuous depositional works by those rivers are responsible for the development of recent piedmont fans. Strong topographic influences and excessive sedimentation processes have developed fast widening (Table 8.2) and scouring nature of several parallel river channels.

Bhabar Zone (200–300m)

At the southern part of dissected lower Siwalik zone, Bhabar area is located. It is comparatively a narrow tract situated in between lower Siwalik and Terai zone (Fig. 8.7). In this zone Ganga channel is characterized with boulders, cobbles, pebbles, and sands. The author has witnessed different types of channel behaviors in this zone like dry river channel, channel avulsion, channel shifting, flash flood (during monsoon), etc. In the rivers of the physiographic zone due to frequent diversion of channel, villages located along the riverbank face channel shifting-



Fig. 8.6 Left side photograph indicates active soil and gully erosion along the non-perennial channel in Bhabar zone near Sureswari temple and Ranipur forest range. Right side photograph shows very wide and unconfined braided channel of Ganga near Ballawali. (Source: field survey, May 2008)

associated problems. The author has also identified active soil and gully erosion (Fig. 8.6) along some parts of different riverbanks like Ranipur Rao, Ganga, etc.

Terai Zone (Less Than 200m)

Terai is the southern extensive physiographic division of the study area (Fig. 8.7). Laksar city is located in the zone within 200 meter altitude, where a vast wide-braided channel of the river Ganga is observed. Here Solani river joins with Ganga River, and a vast wetland has been developed at the Solani-Ganga confluence. Near Bishanpur a different branch of Ganga River is observed, and after its 45-km journey, it joins again with the Ganga. The confluence zone of Banganga and Ganga is basically a vast water-flooded area. Hence, a riverine wetland ecosystem prevails here. This wetland ecosystem is situated in Laksar range, and it is called Banganga wetland. Near Ballawali the Ganga River channel is characterized with an extensive braided pattern (Fig. 8.6) mainly filled with coarser and finer sands and silt. In this zone floods occur every year during the monsoon period. Besides flood, shifting of channel and channel avulsion are the major geomorphic hazards of the area. Villages situated in these areas face huge loss of property due to these hazards. Roorkee city is also situated at the transitional zone of the Bhabar and Terai.

8.3.2 *Aggrading Characteristics of the Ganga and Its tributaries*

As the study area is a part of upper Ganga plain, channel sedimentation is a common feature in Ganga and its other tributaries. In Bhabar and Terai zones, the formation of several channel bars is the strong geomorphic evidence of aggrading nature of channel. At the southern part of Haridwar district (Terai zone), a prominent braided

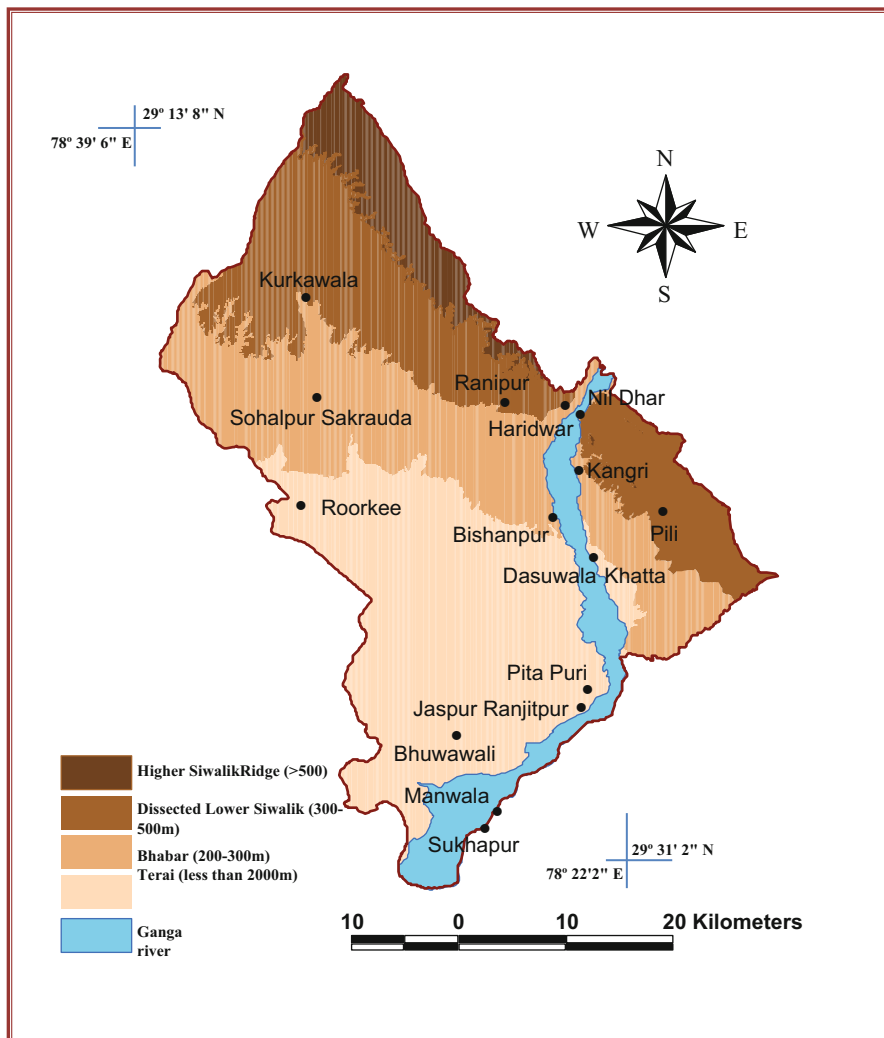


Fig. 8.7 Major physiographic divisions of the study area. (Source: prepared by the author)

channel is observed from the satellite image (Fig. 8.8). The braided channel pattern stands for aggrading Ganga River system. Aggrading Ganga river channel in Haridwar district is one of the causes to enhance channel dynamics.

Impacts of Sedimentation on Channel Bars

The rivers draining the study area (Siwalik to Terai) exhibit significant channel sedimentation process that are reflected in the form of numerous channel bars in the

Fig. 8.8 LISS IV image of Ganga River indicates extensive braided channel in downstream (near Laksar) and in upstream (near Haridwar) comparatively confined channel observed due to structural control. (Source: LISS-IV, 2005, NRSC)



entire Ganga River course of Haridwar district (Sinha, 2005). The researcher has vigorously studied the impact of sedimentation on Ganga River channel bars. The number of channel bars in Ganga River counted by author from topographical sheets in 1967 (SOI, 1967) were 180, and in 2005, the number of channel bars identified from the satellite image (LISS III, 2005) were 134. So it is very clear that the number of channel bar is declining from 1967 to 2005, and the researcher has also studied that the area of most of the bars are gradually increasing with their size. So, from this investigation, it is very clear that the declining number and gradually increasing size of the bars clearly indicate rapid channel deposition. Sandbars along the Ganga River are observed with occasional changes due to floods. The dynamic nature of the channel bars has a great influence on the flow properties of several primary and secondary channels of the Ganga River.

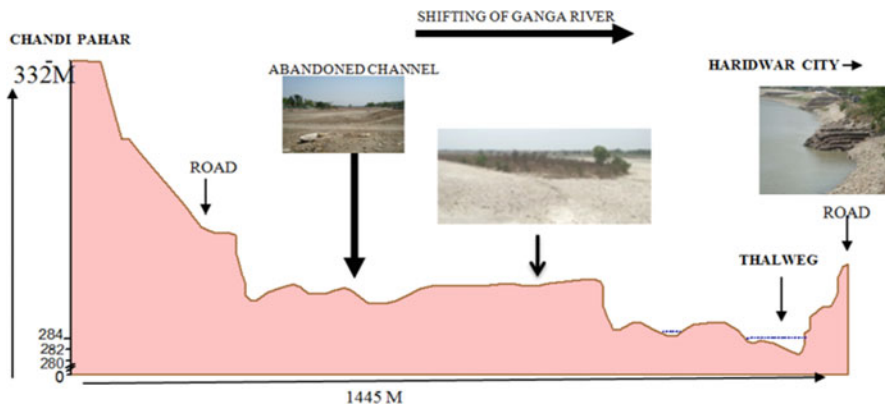


Fig. 8.9 Cross-section of Ganga River channel near Chandi bridge, showing abandoned channel, mid-channel bar, terrace, and sifting nature (toward the right bank) of the active Ganga channel. (Source: field survey by the author, May 2008)

Channel Forms in the Cross-Section of Ganga River

For the vivid analysis about channel dynamics of Ganga River, a cross-sectional (Fig. 8.9) study is very relevant. Therefore, a vast cross-section (about 1500 m) of Ganga River channel in between Mansa and Chandi hill valley has been studied. Geomorphologically, the entire cross-sectional area is under a vast river valley characterized with abandoned channel (Fig. 8.9), dry channel, lower alluvial terraces, stable mid-channel bar, unstable channel bars, thalweg, etc. In the present channel, stable and unstable bars are very evidently observed. The thalweg line of Ganga River is shifting toward the west direction. At present the thalweg line is in the extreme west side of the channel. The shifting of thalweg line toward Haridwar city is a serious issue. Man-made embankment with boulders was constructed to protect the city, but the effort is not enough. Serious damages in some parts of the embankment are caused by riverbank erosion.

Channel Abandonment and Development of Stable Mid-Channel Bar in Ganga River

An abandoned channel in a cross-section is a strong geomorphological evidence of the shifting nature of Ganga channel. It is situated below the Chandi bridge, and it is located on the left bank (Nildhara area) of the river Ganga (Fig. 8.9). Along the abandoned channel, avulsion occurs during every monsoon.

In the abandoned channel area, a very interesting relationship has been noticed by the researcher between channel morphology and riverbank erosion. Along the left bank of the Ganga, severe riverbank erosion is noticed, but on the right bank of the Ganga River, bank erosion problem is not so serious as some protective engineering

measures have been taken. If the erosion is not properly managed, in the future, the problem of erosion on the right bank may be a more serious issue than the bank erosion problem of the left bank, because the main Haridwar city is located on the right side (Fig. 8.9) of the Ganga River and at present the shifting trend of the active channel is toward the city.

Bank erosion scenario along the left bank of the Ganga River is totally different than its right bank. In spite of the excessive erosion along the left bank during monsoon period, no effective preventive measures have been taken by the local authority from 2006 to 2017. Every monsoon, a serious erosion takes place due to shifting and avulsion of channel over the left bank.

The investigator surveyed the study area in the month of October 2010, after a flood, and found some remarkable impact of flood on riverbank erosion. Along the left bank, more than 500 meters south from the Chandi bridge, the top soil layer is totally washed away, and about 40 meters along the bank, it is totally eroded away.

The author has identified a crucial reason of riverbank erosion on the left bank. In this part due to rapid channel sedimentation, a vast mid-channel bar (Fig. 8.9) has been developed, which is increasing in size very rapidly and becoming a stable bar covered with trees and bushes.

The growing size of the mid-channel bar is an important reason to enhance the bank scouring and avulsion nature of Ganga channel. The researcher has analyzed the dynamic nature of the mid-channel bar with the help of primary and secondary data. In 1971 (toposheet, SOI), the area of the bar was 6.31 ha. In the year 1997 (LISS-III), the area of the bar has increased to 11.68 ha. Again the area of the mid-channel bar was measured from the satellite image (LISS-III, 2005), and it was 12.65 ha in the year 2005. The researcher has surveyed the mid-bar with a GPS receiver in the year 2010, October, and then the area has increased to 12.9 ha (Dutta, 2017).

However, from the change detection study, it can be depicted that both size and area of the bar are increasing very rapidly, indicating an active sedimentation on the riverbed.

Sinha (2005) already discussed the growing nature of Ganga channel bars under active sedimentation. Singh et al. (2007) have also mentioned in Haridwar Ganga downstream braided channel with huge sandbars mostly 100–500 m wide and 0.5–5.0 km in length.

As a result, the hydraulic radius of the channel of Ganga is being reduced, and during monsoon excessive water discharge creates unprecedented bank scouring, and the entire events lead to the dynamic nature of the river channel (Fig. 8.10).

8.3.3 Shifting and Avulsion Nature of River Channels

Shifting and avulsion of channel are significant fluvial geomorphic characteristics of Ganga and its tributaries. In sedimentary geology and fluvial geomorphology, avulsion is the rapid abandonment of a river channel and the formation of a new

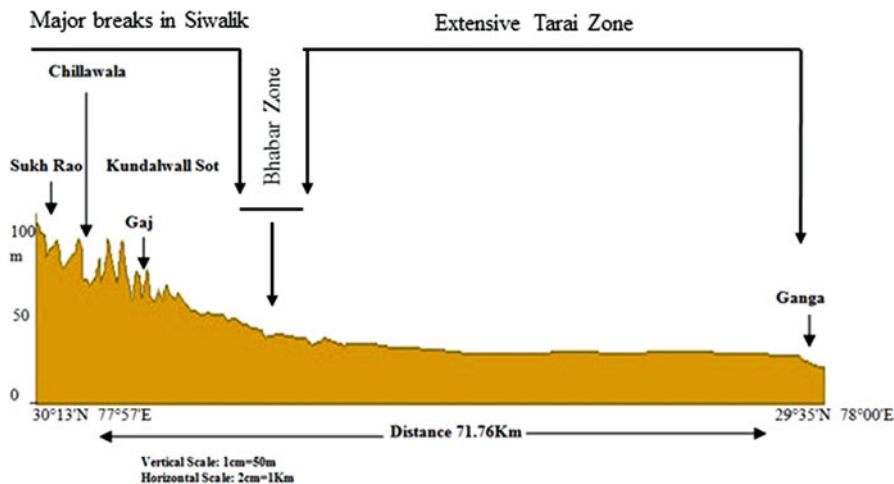


Fig. 8.10 Longitudinal profile from the extreme north (Sukh Rao valley) to the extreme south (Ganga River) of the study area reveals major breaks of slope in the northern Siwalik zone and extensive Terai zone in the south. (Source: prepared by author depending on the toposheets, SOI (1967 and 1971)

river channel. In braided stream mainly three types of avulsions are found: *choking avulsion*, *constriction avulsion*, and *apex avulsion* (Jones & Schumm, 1999).

Different Sites of Avulsion

The author has visited (2006–2017) different parts of the area and identified several types of channel avulsion in Ganga, Solani, Ratmao, Pathri, etc. During monsoon channel avulsion becomes very active mainly in the southern part of the study area. Along the Ganga River, nodal and random types of channel avulsion (Dutta, 2017) are observed. Near Nildhara area nodal avulsion takes place during every monsoon season. This type of avulsion is considered as constriction avulsion that is produced by deflection, confinement, and subsequent diversion of the flow by a bar formation.

Near the village of Tatwala, random avulsion is noticed. This type of avulsion is observed when there is erosion at the outside of sinuous thalweg and confined meander bends.

At the extreme southern part, near Banganga wetland area, some imprint of regional avulsion (Jones & Schumm, 1999) is observed by the author.

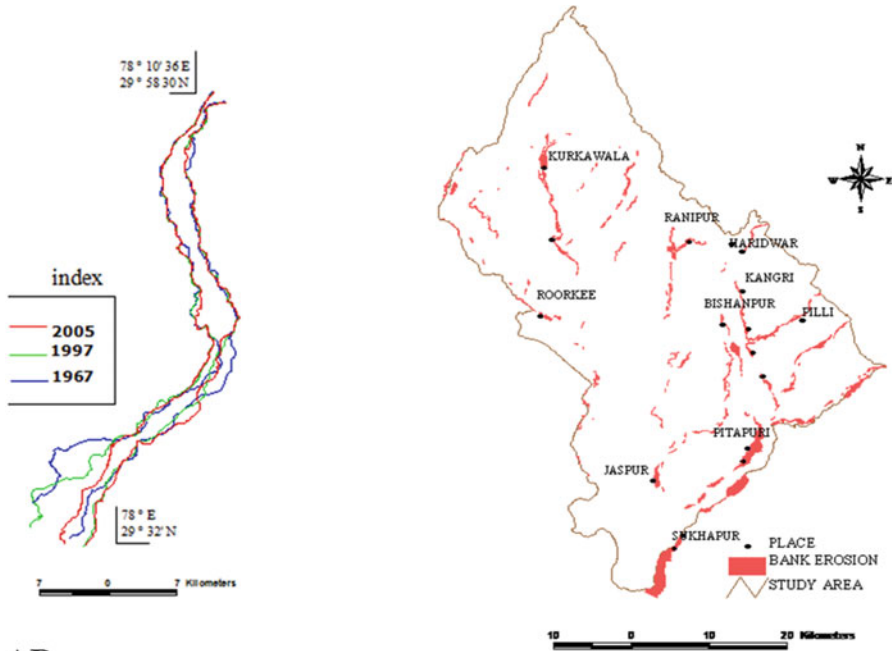
Near Kangri (Bhabar zone), Gajiwali-Shyampur villages (Fig. 8.11), minor random avulsion is observed in the wider Ganga River channel. This type of avulsion is a choking avulsion which is caused by blockage of one channel by a sediment lobe. All types of avulsions in the study area take place during the monsoon season.



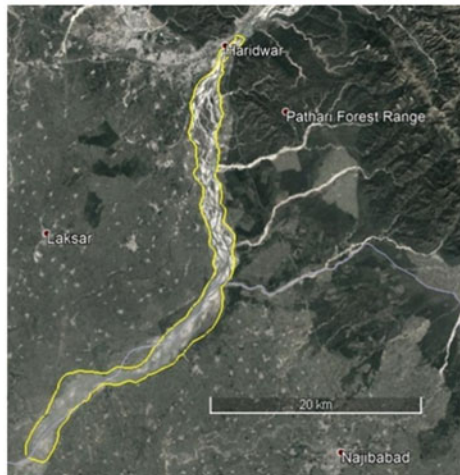
Fig. 8.11 From Google Earth satellite image. An extensive dynamic braided pattern of Ganga River shows several random avulsion courses near flood-prone Kangri and Gajiwali-Shyampur villages. (Source: field survey with GPS receiver on 19 February 2017)

Change Detection Study on Shifting and Avulsion of Ganga and Other Rivers

The study area is characterized with channel shifting and channel avulsion in major rivers such as Ganga (Fig. 8.12b), Solali, Ratmao, Patri, etc. (Fig. 8.1). During monsoon, channel avulsion becomes very active, mainly in the southern part of the study area of Ganga River. For the better understanding of channel shifting of Ganga River, the present researcher has studied the river channels from 1967 (toposheet, SOI) to 2005 (LISS-III). From the change detection map (Fig. 8.12a), it is very evident that in the southern portion of the study area (Terai), the tendency of channel shifting and avulsion is very high in all the abovementioned rivers. The riverbank-eroded area is measured by the author to be about 49.30 sq km (Fig. 8.12b) from 1967 to 2005. That reveals a maximum channel instability in the Terai zone compared to the Siwalik area of Haridwar. This sharp channel instability causes great loss to agricultural land and road network of Terai zone. Based on recent satellite image (May 2020), it is evident that (Fig. 8.12c) several secondary channels and braided bars appeared along Ganga River in Haridwar. The area of the braided Ganga River in 2020 is measured to be about 102 sq km. In that image, the width of



AB



C

Fig. 8.12 The left one (a) expresses the shifting nature of the entire Ganga River channel (from 1967 to 2005) in Haridwar district, emphasizing unconfined channel in Terai and, on the other hand, Siwalik structure and human-controlled narrow channel in Siwalik zone. The right one (b) indicates a bank-eroded area (about 49.30 sq km) by Ganga and its tributaries (from 1967 to 2005). (Source: toposheets-1967, LISS-III, 1997 and 2005). The yellow line on the satellite image (c) shows the outline of Ganga expressing prominent braided river channel. (Source: Google Earth image, May 2020)

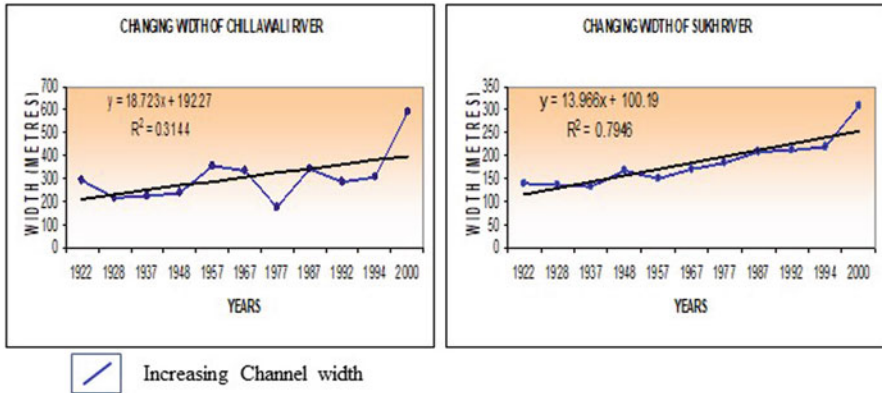


Fig. 8.13 Time series graph and trend lines indicate increasing channel width (1922–2000) in Chillawali and Sukh rivers in Rajaji National Park, Haridwar. (Source: based on data by Kumar, 1995)

the river at the extreme south is comparatively lesser (May) than the 2005 LISS-III image (November). So, the channel width of Ganga River varies with season (pre- and post-monsoon) (Fig. 8.13).

8.3.4 Observation of Flood-Induced Channel Avulsion

During field verification, the researcher has observed flood-induced channel avulsion in 2010 and 2013. It should be understood that the instability of a channel (i.e., avulsion threshold) caused by different factors (excessive sedimentation, meandering, braided channel course, variability, magnitude of discharge, etc.) does not necessarily induce avulsion unless a triggering event like flood or tectonic tremor occurs (Heller & Paola, 1996). It, therefore, follows that avulsion frequency would depend on how the processes inducing channel instability interact with the triggering events (Jones & Schumm, 1999). Mukhopadhyay (2010) rightly stated that the fundamental cause of avulsion is the relative loss of sediment-fluid carrying capacity of a channel to such an extent that the existing path becomes unfavorable for sustaining the flow, and the channel then finds a new course along a favorable gradient. There is no doubt that flood is the triggering factor for random avulsion in the braided channel of the Ganga River’s course toward the southern part of Haridwar, because it is observed by the researcher during field verification that the occurrences of avulsion took place in flood situation of 2010 and 2013. During 2010, flood-induced channel avulsion seriously damaged a permanent road below the Chandi bridge where an abandoned channel have been identified by Dutta (2017). In 2010 and 2013, due to a flood, new micro-channels (Figs. 8.14 and 8.16) have been developed along the left bank of Ganga, below of Chandi bridge. In the 2009–2010 flood, about 69 villages were badly damaged.



Fig. 8.14 Development of a new avulsion channel, below Chandi bridge during the 2010 flood (field survey, October 2010)

Variability of Water Discharge and Flooding Nature of the Rivers

The variability of water discharge is one of the controlling factors of the dynamic nature of river channels of the area. In Haridwar riverbank erosion is caused by a heavy fluctuation of stream discharge. Except Ganga, all of the rivers are non-perennial in nature, and that is why during dry season in many rivers, water flow does not appear, but in the period of monsoon, water discharge suddenly increases many times, and the excessive water flow enhances fluvial erosion power. As a consequence, sudden unprecedented flow induced bank scouring; shifting and avulsion are prominently noticed. The variation in water discharge (maximum and minimum water discharge at Rishikesh) in Ganga River is observed with seasonal change also. The maximum water discharge observed during July–August 2001 is about 3500 cumecs, and the minimum water discharge noticed during December–February is below 500 cumecs.

During monsoon period, flood occurs, and sometimes prolonged rainfall creates flash flood in mountainous streams. In the year 2010, during July–August, excessive monsoon rainfalls (1516 mm. up to 25 September) caused a major flood in the area. Heavy and continuous rainfall took place in the district for 3 days. High flood was observed in Ganga and in other local/regional rivers and rivulets. Breach in

embankments of rivers, rivulets, and canals was noticed. More than 6 lakh cusecs of water discharge by Ganga River was reported in Laksar continuously for 35 hrs. The water discharges from different rivulets/rivers were as follows: Sonali river (25,000 cusecs), Ratmao (55,000 cusecs), Pelli (30,000 cusecs), and Pathari Roa (25,000 cusecs). Even in Ganga River, a massive flood took place in different years like 1910, 1924, 1978, 1995, 1997, 2010, and 2013. In those years, the maximum flood peaks were more than 4 lacks. During lean period the channels of almost all tributaries are observed as dry channel. So extreme variability of discharge in Ganga River and its tributaries is the main influencing factor of river dynamics in the area.

Apart from the variability of water discharge, the magnitude of water flow directly influences channel dynamics of Ganga and its other tributaries. It is said that when water level rises more than 1 meter than the danger level (DL) of a gauge site, then the flood is considered as a major flood (Dhar & Nandargi, 2004). Based on collected flood data from the DM office, Roshnabad, Haridwar, it is found that from 1894 to 2010, nine major flood peaks in Ganga River have been observed in the area, but since the year 1995, the occurrence of the major flood is observed every 1 or 2 years interval. It means the occurrence of major flood is rising gradually. The danger level for the gauge site of Haridwar is 294.00 meters. On 3 August 1997, a major flood occurred in Haridwar with the flood level of 295.35 meter. The difference between danger level and flood level was 1.35 meter (Dhar & Nandargi, 2004). At Haridwar, the river annually discharges $21,393 \times 10^6 \text{ m}^3$, of which 75% flows during the monsoon period (June to September) and 25% is distributed during the remaining part of the year. The average discharge of the river is over $1523 \text{ m}^3/\text{s}$ during the monsoon period and decreases to $282 \text{ m}^3/\text{s}$ in winter. In 2009–2010, about 69 villages of Haridwar district were flooded. This year, the Ganga River flooded the villages of Kangri, Gajiwali-Shyampur, Sajanpur Pili, Rasulpur, Mithiberi, Tatwala, Bishanpur, etc.

Impact of the 2013 Flood on Channel Geomorphology

The present author has visited the area on October 2013 and observed some remarkable changes about channel forms. Deposition of fresh sediments on the riverbed (Fig. 8.15) is distinctly observed in Ganga River. Numerous uprooted trees have blocked some parts of the channel of Ganga and other tributaries. Near Nildhara area, a number of new channel bars have been developed under the influence of fresh channel sedimentation. During the high flood, massive water flow has created serious soil and bank erosion. The settlement and transport system were also badly affected by flood and flood-associated bank erosion (Fig. 8.16).



Fig. 8.15 Fresh sediment supply in Ganga channel after the 2013 flood. (Source: Field survey, October, 2013)



Fig. 8.16 A newly developed channel along the left bank, at Haridwar, after the flood hazard in Ganga River, Nildhara area. (Source: Field survey, October, 2013)

8.3.5 Anthropogenic Impacts on Ganga River Channel

The construction of the upper Ganga canal and Bhimgoda barrage has created control on channel width (Fig. 8.17) in Mansa and Chandi hill valley. This man-made-confined channel has increased channel instability in downstream Ganga.



Fig. 8.17 Bhimgoda barrage at Haridwar to divert Ganga water into the upper Ganga canal, influencing excessive channel sedimentation and interruption in channel equilibrium. (Source: field survey, February, 2010)

Wolman (1967) showed that the changes of land use can affect sediment yield in a river. Urbanization of the part of the catchment can increase sediment load by several hundredfold. The author reasons that reservoir can greatly influence the longitudinal profile of a river. The aggradational characteristics are seen in the longitudinal profile above the reservoir and erosion immediately below the sluice gates. Aggradation appears again further downstream of the barrage. Morisawa (1985) also stated that the indication of adjustment is seen by the hydraulic geometry which is different from the above and below the dam.

It has been found that Bhimgoda barrage and upper Ganga canal have greatly influenced the normal equilibrium of the Ganga River. The construction of upper Ganga canal was conceived and constructed by Proby T. Cautley during the period 1840–1854 (<http://planningcommission.nic.in/reports/sereport/ser/ugc/ch1.pdf>). In the beginning one of the branches of the river – a natural channel flowing near Haridwar – was used to divert practically the entire winter flow by constructing temporary obstructions across other branches. The upper Ganga canal takes off from the right flank of Bhimgoda barrage which replaced the old weir at Haridwar in 1991–1992.

The barrage (Fig. 8.17) ($29^{\circ} 57' 23''\text{N}$, $78^{\circ} 10' 49''\text{E}$) is 455 m (1493 ft) long and has the head of a 23,000 km² (8880 sq mi) catchment area. It contains 15 spillway gates and 7 under sluice gates, 18 m (59 ft) wide all in all. The flood discharge of the barrage is 19,300 m³/s (681,573 cu ft/s). Adjacent to it, on the right bank of the river,

the barrage diverts water into the upper Ganga canal. The canal system is immense, consisting of 6450 km (4008 mi) of main canal and branches, providing irrigation for up to 2,023,000 ha (4,998,942 acres) land.

The photographic evidences of Bhimgoda barrage clearly indicate excessive siltation at upstream and downstream courses of the barrage (Fig. 8.17). Undoubtedly, the barrage has disturbed the natural longitudinal profile of the Ganga channel. The upstream and downstream of the barrage channel aggradation in the Ganga River has enhanced channel instability.

Besides this, channel materials (boulders, pebbles, sands), mining in Ganga, and other tributaries have significant impacts on channel behaviors. Sometimes unscientific channel excavation increases channel roughness that creates discontinuity of channel flow or eddies. These types of anthropogenic intervention directly and indirectly enhance the dynamic nature of Ganga River.

Ganga River channel courses and a number of channel bars are intensively utilized for the temporary tent for the pilgrims (Fig. 8.18) during Kumbh Mela and other religious festivals. Therefore, the natural vegetation of the channel bars are totally obliterated, and the stability of those channel bars is disturbed by anthropogenic effects. However, the human-induced wastages are removed into Ganga River unintentionally. These wastage materials seriously accumulate the human-induced sediments into the Ganga River. If it continues, there is no doubt the channel instability would increase day by day.



Fig. 8.18 Temporary tents and shelters for pilgrims over Ganga channel course, near Chandni bridge. (Source: field survey, February, 2010)

8.4 Conclusion

From the above discussion, the authors have come to the following conclusions.

River dynamics are evidently expressed in various channel behaviors like channel sedimentation, avulsion, channel abandonment, meandering and braiding, channel shifting, bank erosion, etc. of Ganga and its tributaries.

The varied channel behaviors are influenced by several physical factors like geology and tectonics, geomorphology, occurrence of flood, channel sedimentation, etc. and anthropogenic factors like Bhimgoda barrage, upper Ganga canal, channel material mining, Kumbh Mela, and other festivals.

Different physiographic divisions have distinct impacts on channel forms.

The area consists of significant landforms (alignment of river channels, channel escarpments, incised meander, river terraces, etc.) under megafan, piedmont fan, river valley terrace, and active flood plain surfaces that indicate strong tectonic influence on the channels.

The change detection map of the Ganga from 1967 to 2005 and the outline of the Ganga (2020) clearly reveal that toward the southern direction (mainly Terai zone), the tendency of shifting and avulsion is comparatively higher than the northern Siwalik zone and the fluvial processes varies on pre- and post-monsoon condition. In the study area, channel instability is increased in the downstream area. As a consequence, villages located in the downstream area face different river channel instability-associated hazards like avulsion, shifting, bank erosion, flood, etc.

The construction of Bhimgoda barrage and upper Ganga canal has greatly influenced the longitudinal profile of the Ganga River. Those constructions have confined the Ganga River channel width in Mansa and Chandi hill valley, resulting in channel instability in the downstream. The barrage accelerates channel aggradational rate, enhancing channel instability. Excessive excavation of materials from the riverbed has also disturbed the natural equilibrium of the Ganga River channel.

References

- Dhar, O. N., & Nandargi, S. (2004). Flood in North Indian river systems. In *Copping with natural hazards: Indian Context* (pp. 104–111). Orient Longman private Limited.
- Dutta, R. K. (2017). Controlling factors of channel shifting and avulsion in Haridwar district, Uttarakhand, Geographical Review of India. *Geographical Society of India, Kolkata*, 79(20), 153–167.
- Field, J. (2001). Channel avulsion on alluvial fans in southern Arizona. *Geomorphology, Elsevier*, 37, 93–104.
- Heller, P. L., & Paola, C. (1996). Downstream changes in alluvial architecture: an exploration of the control on channel stacking pattern. *The Journal of Sedimentary Research, Society of Sedimentary Geology*, 66(2), 297–306.
- https://www.nrsc.gov.in/EOS_dissemination_Order
- Jones, L. S., & Schumm, S. A. (1999). Causes of Avulsion :An overview. *The International Association of Sedimentologists*, 28, 171–178.

- Kale, V. S. (2002). Fluvial geomorphology of Indian rivers: An overview. *Progress in Physical Geography, Arnold*, 26(3), 423–456.
- Kumar, D. (1995). Rajaji National Park, Dehra Dun: Why it is not in sustainable position-remedies for its sustainability. *Himalayan Geology, Wadia Institute of Himalayan Geology*, 6(2), 95–110.
- Morisawa, M. (1985). *Rivers – Form and Process*. Longman Inc., New York.
- Mukhopadhyay, S. C. (2010). Fluvial processes with special reference to avulsion in the flood plains of the Unstable Mahananda-Sankosh interfluvial areas, West Bengal. *Indian Journal of Landscape System and Ecological Studies, ILEE*, 32(2), 521–538.
- Shukla, U. K., & Bora, D. S. (2003). Geomorphology and sedimentology of Piedmont zone, Ganga Plain, India. *Current Science*, 84(8), 1034–1039.
- Shukla, U. K., Singh, I. B., Srivastava, P., & Singh, D. S. (1999). Paleocurrent patterns in braid-bar and point-bar deposits: Examples from the Ganga river. *International Journal of Sediment Research*, 69, 992–1002.
- Shukla, U. K., Singh, I. B., Sharma, M., & Sharma, S. (2001). A model of alluvial megafan sedimentation: Ganga Megafan. *Sedimentary Geology*, 14, 243–262.
- Singh, I. B. (1996a). Late Quaternary sedimentation of Ganga plain foreland basin. Proc. Symp. NW Himalaya and foredeep. *Geological Survey of India Special Publication*, 21, 161–172.
- Singh, I. B. (1996b). Geological evolution of Ganga plain-an overview. *Journal of the Palaeontological Society of India*, 41, 99–137.
- Singh, I. B., & Rastogi, S. P. (1973). Tectonic framework of Gangetic alluvium, with special reference to Ganga River in Uttar Pradesh. *Current Science*, 42, 305–307.
- Singh, M., & Singh, I. B. (1992). The Ganga River Valley: Alluvial valley in an active foreland basin. In *29th International Geological Conference, Kyoto*, 2 (p. 30). Japan.
- Singh, M., Singh, I. B., & Müller, G. (2007). Sediment characteristics and transportation dynamics of the Ganga River. *Science Direct, Elsevier, Geomorphology*, 86, 144–175.
- Sinha, R. (2005). Why do Gangetic rivers aggrade or degrade? *Current Science*, 89(5), 836–839.
- Srivastava, P., Singh, I. B., Sharma, M., & Singhvi, A. K. (2003). Luminescence chronometry and Late Quaternary geomorphic history of the Ganga Plain India. *Palaeogeography, Palaeoclimatology, Elsevier Palaeoecology*, 197, 15–41.
- Uniyal, A., Ravindran, K. V., & Prasad, C. (2010). Tectonic control on alluvial fans, piedmont streams and Ganga River in western Ganga Plain (India) using satellite remote sensing data. *Current Science*, 99(1), 91–97.
- Valdiya, K. S. (2003). Reactivation of Himalayan frontal fault. *Current Science*, 85(7), 1031–1040.
- Wolman, M. G. (1967). Two problems involving river channel changes and background observations. *Northwest University Studies in Geography*, 14, 67–107. <http://planningcommission.nic.in/reports/sereport/ser/ugc/ch1.pdf>; https://en.wikipedia.org/wiki/Bhimgoda_Barrage