The Ganga River: A Summary View of a Large River System of the Indian Sub-Continent

S.K. Tandon and R. Sinha

1 Introduction

For thousands of years, civilizations have taken root and prospered in the south Asian region, leading up to a population 'hot spot' accounting today for almost a sixth of the globe's population. Rivers, more so large river systems, have constituted the fundamental basis for sustaining the civilizations of this region. Most importantly, three large rivers—the Indus, the Ganga, and the Brahmaputra—have together contributed to the building up of extensive fertile alluvial plains that add up to an area of well over a million square kilometers, which were extensively used by humans over the millennia. Indeed, the Indus–Ganga–Brahmaputra (IGB) plains constitute a significant part of some of the world's largest water and sediment routing systems such as the Himalaya–Bengal–Nicobar and the Himalaya–Indus submarine fan systems that originated as a consequence of the post-Himalayan uplifts.

2 Drainage Organization, River Course, and Major Urban Settlements

The Ganga, one of the largest river systems on the globe, originates at Gaumukh at an elevation of ~ 3800 m near the Gangotri Glacier and traverses a length of 2525 km through eleven states of northern and eastern India, until it meets the sea in the Bay of Bengal (Fig. 1).

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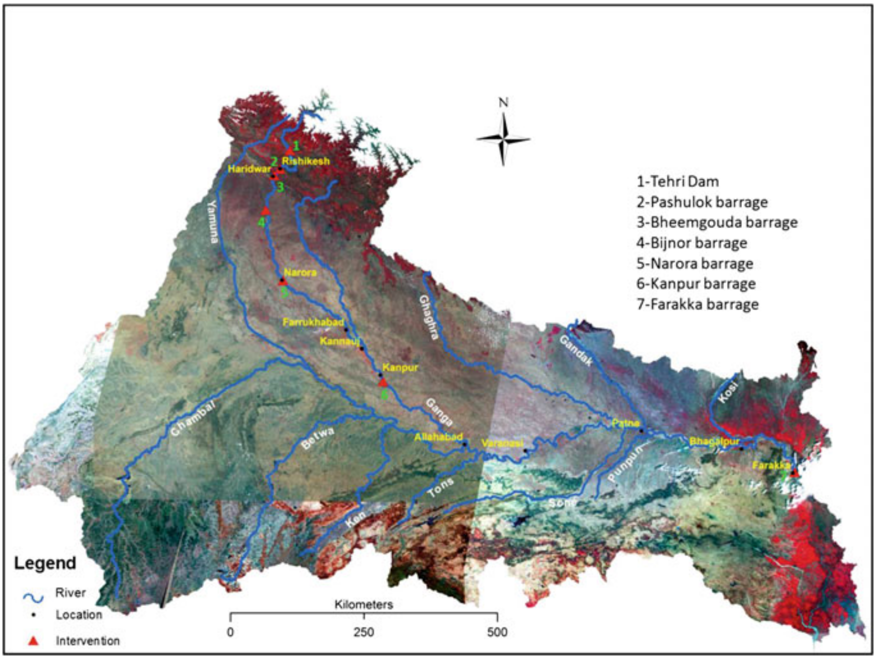


Fig. 1 Course of the Ganga river and major tributaries; major urban centers are also shown

The headwaters of the Ganga are constituted by the Bhagirathi and the Alaknanda, which join at Deoprayag in Uttarakhand. Besides, there are four other headwater streams, namely the Dhauliganga, Nandakini, Pindar, and the Mandikini (Fig. 2).

The Ganga continues its journey in the Himalayan hinterland downstream of Deoprayag, exits the mountainous terrain at Rishikesh, and a few kilometers further downstream debouches on to the proximal part of the Ganga Plain at Haridwar, a town of immense cultural and religious significance. From here onward, the river is oriented toward the southeast for over 800 km until its journey to Kannauj, Farukkhabad, and Kanpur. At Kannauj, the Ganga is met by the Ramganga with an average annual flow of about 500 m^3/s. Further downstream of Kanpur, the Yamuna and the Ganga join at the Triveni Sangam at Allahabad, where the latter contributes 2950 m^3/s (Jain et al. 2007), or $\sim$58.5% of the combined flow. Notwithstanding the importance of many of the other major tributary confluences in the system, this confluence of the Yamuna and the Ganga is perhaps the most unique as the Yamuna's discharge has a large volume of water and sediment that has been collected from rivers flowing from the hinterlands of the cratons to the

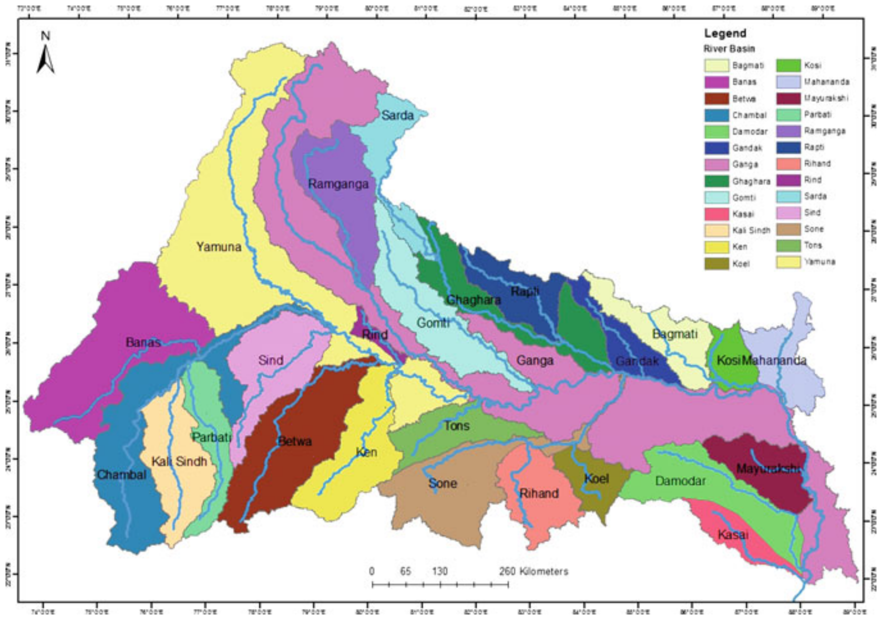


Fig. 2 Sub-basins in the Ganga river system

south; these rivers flowing from the south include the Chambal, Sind, Betwa, and the Ken, the latter two having been linked by a river-interlinking project.

Downstream of Allahabad, the river flows eastward, is met by the Tons, Son, and the Punpun from the south, and the Gomti, Ghagara, Gandak, and Kosi rivers from the north. Annual average flows of the peninsular-sourced rivers—the Tons and the Son—are 190 and 1000 m^3/s, whereas those of the Himalayan-sourced Gomti, Ghaghara, Gandak, and Kosi are 234, 2990, 1554, and 2166 m^3/s, respectively. Downstream of Allahabad, the river takes an easterly course and continues its journey to Patna via Mirzapur and Varanasi, the latter city being the most important cultural and religious center in the region. Varanasi is also one of the oldest cities and was known as Kashi in ancient India. Beyond Patna, the Ganga traverses through the volcanic rocks of the Rajmahal Hills, before entering the deltaic area near Farakka, close to the border with Bangladesh. Near Pakur, the river branches into its first distributary channel, the Bhagirathi-Hooghly. The Hooghly River is fed by the Bhagirathi and the Jalangi rivers that meet at Nabadwip. Also, the Hooghly is joined by tributaries that flow from the southeast; these include the Damodar, Rupnarayan, Ajay, and Haldi. The largest of these, the Damodar is 541 km long and has a drainage basin of $\sim$25,800 km^2 (Fig. 3).

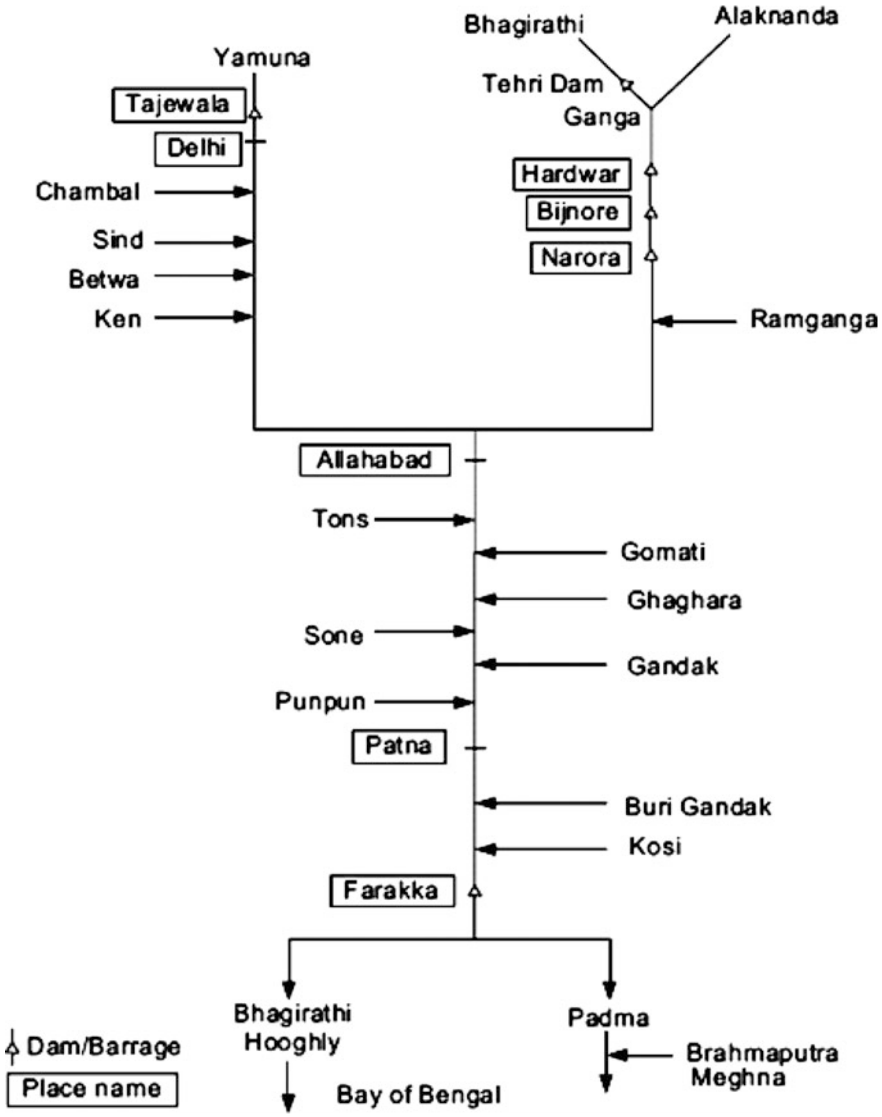


Fig. 3 Line diagram of the Ganga and its major tributaries (adapted from Jain et al. 2007)

3 Geomorphology, Hydrology, and Soils

After flowing through a mountainous valley, the Ganga flows into the Himalayan foreland, the upper most part of which is represented by vast low relief plains. In the central part of the Indus–Ganga–Brahmaputra plains, the Ganga Basin formed as a

NE–SW-oriented elongate depression that is bounded to the north by the Himalayan thrust sheets, and over significant areas in the south by the Bundelkhand and cratons (Sinha and Tandon 2014). The basin accounts for almost a quarter of India's landmass, 30% of the water resources, and supports almost 40% of India's population.

The depth to the basement in the plains is variable from a few kilometers to a few tens of meters toward its southern margin. The Ganga plains have been built by two distinct hinterlands—the Himalaya in the north and the cratons to the south (Sinha et al. 2009). Sinha and Tandon (2014) indicated that the mountain-fed tributaries of the Ganga such as the Yamuna, Ramganga, Ghaghara, Gandak, and Kosi are commonly braided systems with relatively higher discharges than those of the sinuous foothills-fed and plains-fed rivers.

The Ganga trunk channel shows variable patterns, braided–low sinuosity meandering being a common pattern. Some reaches of the Ganga, for example, that between Allahabad and Varanasi show a meandering pattern; similarly, the Yamuna after meeting the Chambal also shows a meandering pattern due to the increased hydrological and sediment inputs being routed through the Chambal from the cratonic highlands (Sinha and Tandon 2014). Throughout the plains, several of the smaller plains-fed rivers exhibit high sinuosity meandering patterns.

On the basis of hinterland types (Himalayan and cratonic), hinterland-basin interactions, along-strike geomorphic variability, and sea-level controls, Tandon et al. (2008) proposed the following simple classifications of the Ganga dispersal system (Fig. 4):

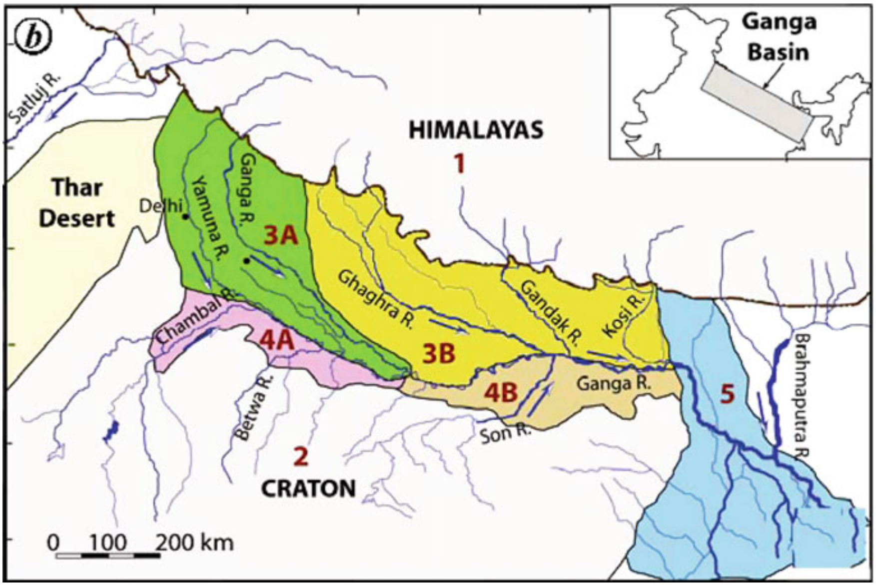
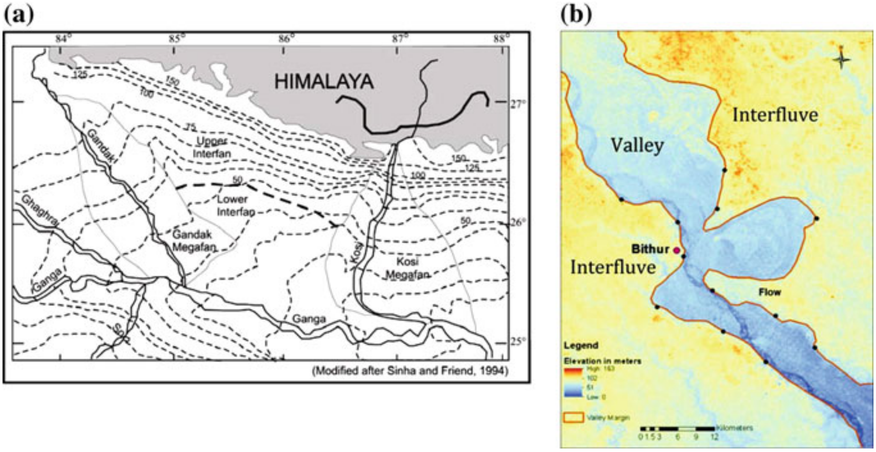


Fig. 4 Stream power-based classification of the Ganga dispersal system (after Tandon et al. 2008)

(1) Himalayan hinterland,
(2) Cratonic hinterland,
(3) Northern Ganga alluvial plains divisible into subcomponents (A) western part made up by tributaries with high-stream power and incised valleys and (B) eastern part made up of rivers with high stream power and aggradational valleys,
(4) Southern Ganga alluvial plains south of the Ganga and the Yamuna made up of tributary systems that are sourced in the cratonic highlands; these are further subdivided in two subcomponents based on the relative incision characteristics of the plains, and
(5) Lower Ganga plains and distributary-delta system south and east of Farakka.

Within and across these major units of the Ganga plains, considerable geomorphic diversity has been noted by the previous workers (Sinha et al. 2005). The main landscape elements include the (a) proximal piedmont zone, (b) main Ganga valley, (c) inactive floodplains and valley margin, (d) major interfluve systems that are elevated tracts, and (e) major tributary domains such as the Chambal and the Kosi. As a consequence of variable along-strike hinterland–basin interactions, the eastern parts of the plains, mostly in Bihar, are dominated by a fan–interfan setting, whereas the western part of the plains is marked by a valley–interfluve setting (Fig. 5) (Jain et al. 2012; Tandon et al. 2008).

Rainfall and subsurface flows are the main sources of water with meltwater from the Himalayan glaciers in the source region constituting a subordinate component, and estimates vary from a fifth to a third of the total water input. Much of the water is received in the Ganga system during the monsoon season from June to September; the mouth of the Ganga begins to receive rainfall in the first week of June, which then gradually advances up to the northern and western parts of the basin during June and July. An examination of the spatial patterns of rainfall shows that the lowest



(Modified after Sinha and Friend, 1994)

Fig. 5 Geomorphic diversity in the Ganga plains. **a** Fan–interfan system in the eastern Ganga plains. **b** Valley–interfluve system in the western Ganga plains precipitation in the basin is in Haryana (~500 mm per annum), whereas in the eastern part of the plains, there is up to ~1600 mm rainfall per annum and even heavier annual precipitation of ~2200 mm in some parts of the adjoining Himalayan hinterland (Fig. 6). Despite the fact that a larger proportion of the catchment area lies in the catchment zones of the peninsular-sourced tributaries, they contribute no more than forty percent of water to the Ganga River System (TERI 2011).

On the basis of average annual discharge, the river systems in the Ganga plains can be divided into two groups, namely large river system and smaller river system. The large river system is mountain-fed stream and includes Yamuna, Ganga in WGP (up to Kanpur), Ghaghra, Gandak, and Kosi. The average annual discharge of these rivers varies from 1500 to 3000 m^3/s. The Ganga River is the trunk river of the Ganga plains, and its hydrological properties downstream of Kanpur indicates the cumulative effects of large river systems, as other large rivers such as Yamuna, Ghaghra, Gandak, and Kosi join it in further downstream reaches. The smaller river systems include the Ramganga, Gomti, Rapti, Burhi Gandak, Baghamti, and Kamla Balan. The average annual discharge of these river systems ranges from 70 to 500 m^3/s. The trunk river Ganga shows increase in average annual discharge from upstream to downstream, which is also accompanied by increase in average sediment load. Sediment load in the Ganga River basin first decreases and reaches to minimum value at Kannauj (15 Mt/year). However, further downstream, the sediment load starts increasing with values of 228 Mt/year at Allahabad and 729 Mt/year at Farakka. This increase is attributed to input from tributaries in eastern UP and north Bihar draining from Nepal. Sinha et al. (2005) reported a

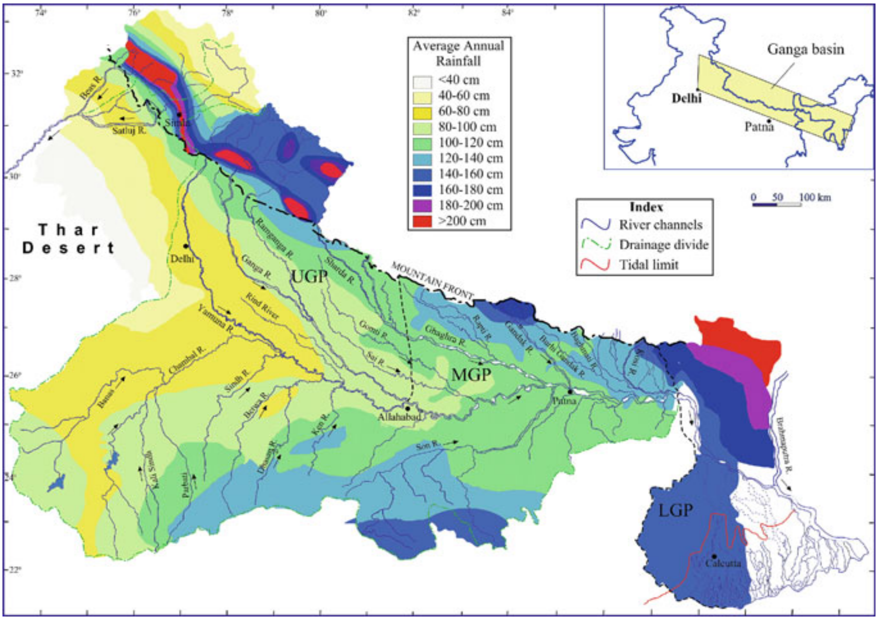


Fig. 6 Spatial distribution of rainfall in the Ganga basin

significant variability in hydrological characteristics of the tributaries of the Ganga River System in the Western and eastern plains manifested in stream power and sediment yield. While the western Ganga plains is characterized by tributaries with high stream power (40–43 W/m^2) and low sediment yield (197–342 t/km^2/year), those in eastern plains show low stream power (6.36–20 W/m^2) and high sediment yield (647–2774 t/km^2/year). It was suggested that this hydrological variability is manifested in geomorphic diversity across the plains.

The Ganga Basin with its vast area of more than 860,000 km^2 in India is characterized by the occurrence of a wide variety of soil types (Fig. 7). Ten classes of soils that include (1) mountain soil, (2) submountain soil, (3) alluvial soil, (4) red soil, (5) red and yellow soil, (6) mixed red and black soil, (7) deep black soil, (8) medium black soil, (9) shallow black soil, and (10) laterite and lateritic soil are developed under the variable lithological, climatic, and morphological conditions developed in different parts of the basin (Mukherjee and Dasgupta 1983, in TERI 2011). The most prominent soil type in the basin is the alluvial soil, covering more than 52% of the basin, which is rich in nutrients and supports a variety of crops such as wheat, jowar, bajra, smaller millets, pulses, maize, cotton, jute among other food and commercial crops.

Because of over-exploitation and intensive irrigation, and the increasing inputs of various fertilizers and agrochemicals, degradation of soil is commonly observed in the form of increased salinity in Haryana, higher alkalinity in western Uttar Pradesh, calcareous soils in Bihar, and soil acidity in West Bengal (TERI 2011).

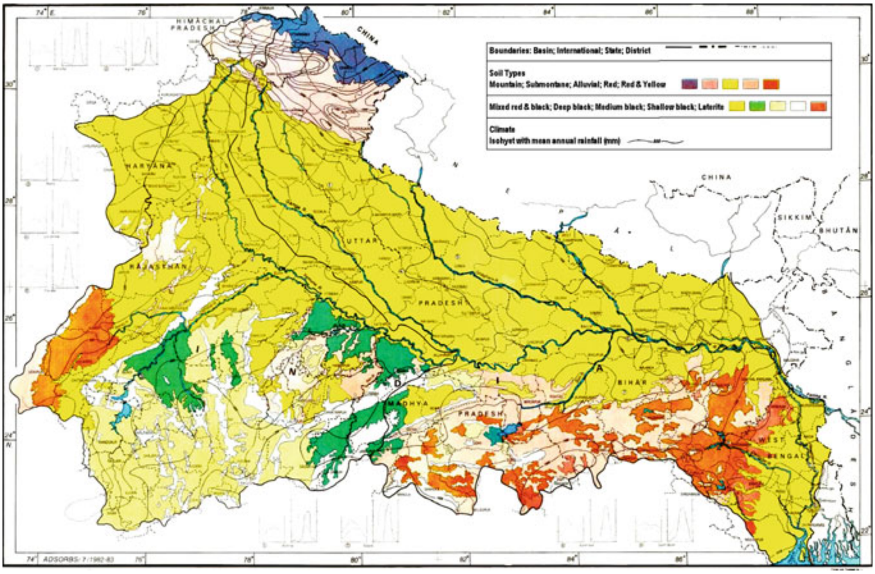
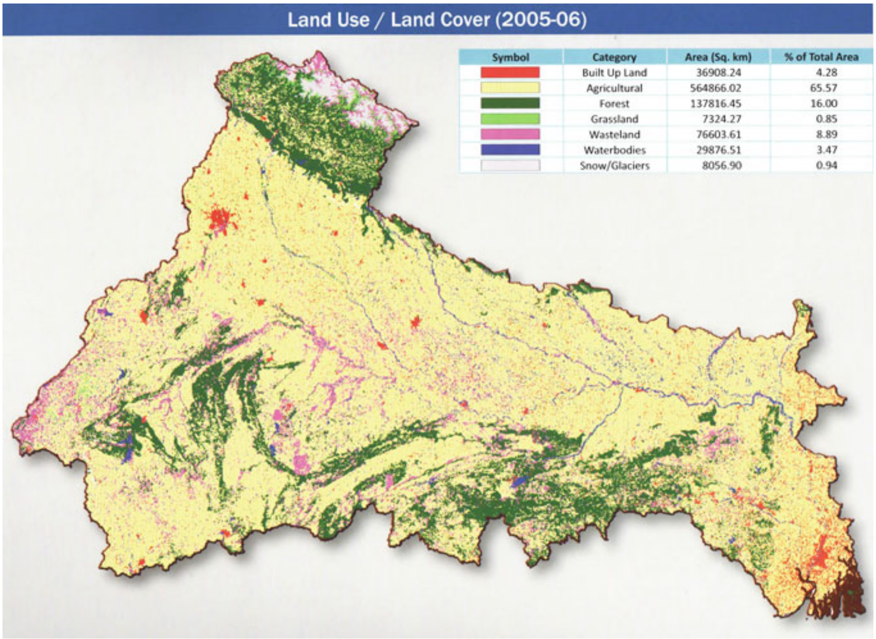


Fig. 7 Soil map of the Ganga basin (*Source* Mukherjee and Dasgupta 1983)

4 Socioeconomic Aspects

The Ganga River System and its basin are of considerable significance from both socioeconomic and sociocultural standpoints, as well as from the aspect of ecological economics. Water abstraction from the Ganga River has been practiced for more than a century and a half via several major canal systems. The Upper Ganga canal originating from Haridwar is 230 km long with a discharge of 300 m^3/s; the lower Ganga canal has a discharge of more than 150 m^3/s. There are more than 600 medium and major irrigation projects that cover a command area of ∼36% of the basin, i.e., 427,226 km^2 (TERI 2011). The major projects, besides functioning as waterways for irrigation, also serve the purpose of flood control during the high flows of the monsoon season.

The net irrigated area in the basin is ∼361,000 km^2; repeated irrigation takes place for raising more than one crop in a year. Human occupation over the millennia and the burgeoning population in the recent decades have resulted in strong pressures on the land; this has resulted in the replacement of most of the natural vegetation by agriculture (Fig. 8).



Symbol	Category	Area (Sq. km)	% of Total Area
🟥	Built Up Land	36908.24	4.28
🟨	Agricultural	564866.02	65.57
🟩	Forest	137816.45	16.00
🟩	Grassland	7324.27	0.85
🟪	Wasteland	76603.61	8.89
🟦	Waterbodies	29876.51	3.47
⬜	Snow/Glaciers	8056.90	0.94

Fig. 8 Land-use/land-cover map of the Ganga basin (CWC 2012)

5 River Hazards in the Ganga Plains

Several rivers draining the Ganga Basin are prone to two major river hazards—river dynamics and floods—and these are intricately interrelated. The dynamics of the rivers is primarily driven by channel instability caused by extrinsic factors such as tectonics or intrinsic factors such as excessive sedimentation and local slope variability. Further, flooding in several rivers such as the Kosi River does not occur as classic overbank flooding due to excess inflow but is generally triggered by a breach in the embankments which have ironically been constructed for flood protection. In most cases, breaches in the embankments are associated with channel instability coupled with human factors such as poor maintenance.

Fluvial dynamics in the Gangetic plains was initially reported by Shillingfield (1893) and followed by several workers. Many of these papers focused on the westward movement of the Kosi River in north Bihar plains. Shillingfield (1893) opined that the progressive westward movement of the Kosi River would be followed by the eastward movement in one great sweep which proved to be true when the Kosi River avulsed by ~120 km in August 2008 (Sinha 2009; Sinha et al. 2014). On an average, the Kosi has shifted by about 100 km in the last 200 years and is related to the shifting process with the cone (megafan) building activity, sediment deposition, rise of bed levels (Gole and Chitale 1966), and the unidirectional channel shifting occurring progressively from one edge of the cone to the other edge. Apart from the major rivers such as the Kosi, the smaller rivers draining the north Bihar plains are equally dynamic. The migration histories of the Burhi Gandak River along with that of the Ganga around Samastipur (Phillip et al. 1989, 1991), decade-scale avulsions of the Baghmati River (Sinha 1996; Jain and Sinha 2003, 2004) are well documented.

Though the rivers of UP plains are not as dynamic as the north Bihar rivers, they do show some channel movement over a long time period. In the area between Bithoor and Kanpur Railway Bridge, the Ganga River shifted from right to the left bank between 1910 and 1945 and this was attributed to the highly irregular shape of the valley in the area, the 1924 flood causing major changes in floodplain and the location of railway bridge on the extreme right of the flood plain. The Ghaghra River in UP plains has also shifted by ~5 km at certain places, on either side of the active channel over a period of seven years between 1975 and 1982, and was related with the neotectonics in the area (Tangri 1986; Srivastava et al. 1994). The Sarda River is characterized by several westward lateral shifts at different places in between Banbasa barrage (Nainital district) and Palliakalan village (Kheri district) (Tangri 2000). Roy and Sinha (2007) documented the upstream and downstream movements of two major confluence points in the Ganga plains, namely the Ganga–Ramganga and the Ganga–Garra confluences over a century-scale period. The net movement of the confluence points was shown to be as large as ~18 km in case of the Ganga–Ramganga confluence, and the major processes influencing the movement of confluence points are avulsion, local movements by cutoffs, river capture, and aggradation.

6 Water Pollution

River water pollution, ecological loss, and degrading health of the Ganga is a matter of the most serious concern; the issue of cleaning up and rejuvenation of the Ganga River is a national priority. As is well known, the river provides large volumes of water for domestic, industrial, and agricultural purposes, apart from serving several cultural and spiritual needs of the population that inhabits the basin. Stressed further by the exponential increase in population, urbanization, industrialization, the intensive use of fertilizers and agrochemicals, and the abstraction and storage of ever-increasing volumes of water, the quality of water of the Ganga River and its major tributaries continues to deteriorate rapidly.

Major sources of pollution include point sources, such as domestic and industrial wastewater discharges, and non-point sources such as runoff from agricultural fields, solid waste disposal sites, and the runoff impacted by various river-front activities such as bathing ghats. The river system is subjected to 3 billion liters of industrial effluents per day. The major sources of industrial pollution are related to the following sectors—pulp and paper (Uttarakhand), metal artifacts (western Uttar Pradesh), sugar and distillery (western Uttar Pradesh), tanneries (Uttar Pradesh, West Bengal), and jute and textiles (West Bengal).

In terms of domestic waste, 179 class 1 cities generate ~11000 MLD of wastewater and 147 class 11 cities generate ~1000 MLD of wastewater (TERI 2011). Highest generation of domestic wastewater along the river Ganga takes place in Kolkata (618 MLD), followed by Kanpur (339 MLD), Patna (249 MLD), Allahabad (208 MLD), and Varanasi (187 MLD) (TERI 2011). The treatment capacity gap is large for most of these cities.

The Ganga Basin states have a load of ~10 million tonnes of chemical fertilizer each year, in addition to a pesticide load of ~21,000 tonnes (TERI 2011). This application of fertilizers and pesticides has grown over the past few decades with the intensification of agriculture; however, the transport and fate of these anthropogenically introduced loads are rather poorly understood.

Under the Ganga Action Plan phases I and II, there have been efforts to increase the sewage treatment plant capacity, particularly in the five states of West Bengal, Bihar, Jharkhand, Uttar Pradesh, and Uttarakhand.

7 Concluding Remarks

The role played by the Ganga River in sustaining and nurturing a substantial part of India's population is commonly encountered in most narratives of river and water in our country and obviously cannot be overstated. The Ganga River and its basin provide critical resources and ecosystem services to eleven states within India, accounting for thirty percent of India's water resources and provisioning life sustaining support in terms of soil fertility, food security, and ecological habitats to both the burgeoning human population and the animal and plant communities. Despite its value as a resource system and its being the provider of invaluable ecosystem services, the Ganga River system is in poor health because of over-exploitation on many fronts by humans including the unsustainable activities that lead to large-scale pollution over large areas of the network and the basin.

Because of the central role played by the Ganga in our life, it has been declared as the national river and has been the subject of several investigations and studies. More recently, the MOEF supported a program on the Ganga River Basin Management Plan (Gangapedia 2012) and this plan identified some fundamental premises for management of the Ganga River. These are as follows:

(a) River must be allowed to flow continuously,
(b) Riverine processes must be understood in terms of both longitudinal and lateral connectivity,
(c) River requires adequate space for its own functions,
(d) River should be recognized as an ecological entity and be allowed to function as such, and
(e) River should be kept free from all kinds of waste.

While it is recognized that these premises are overriding and emphasize eco-hydrological and ecogeomorphological approaches to river basin management, rivers will continue to be used by humans for a variety of purposes, although increasingly under intense scrutiny to eliminate unsustainable methods and practices.

Therefore, river futures ought to be determined on the basis of multi-disciplinary assessments as opposed to single discipline engineering-oriented approaches that are rooted in command and control strategies to the management of river systems.

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