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Rainfall and Flood Studies of the Ganga River Basin in India

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ABSTRACT

The Ganga basin is one of the largest river basins in the northwest to north region of India. Since, the region is located in the foot hills of the Himalayas is the area of highest rainfall in the downstream areas of north India causing severe to unprecedented floods during the monsoon season. Examination of rainfall and flood data for the period 1986 to 2016 showed that among all the Himalayan rivers joining the Ganga from the north, the major contributions come from the Kosi, Ghagra and Gandak and their tributaries joining the Ganga along its course through Gangetic plains. The most frequent flood experiencing states are Bihar, Uttar Pradesh and West Bengal. Frequency of floods was less in the years 1992, 2009, 2012, 2014, 2015 and it was highest in 1987, 1998, 1999, 2001, 2003 and 2013 years. Since all these Himalayan rivers are perennial in nature due to their source being in Himalayan glaciers and ice caps, this water resource can be utilized for power generation wherever the necessary drop in water level is available. The progress and prosperity of this country is very much linked with the harnessing of the waters of these main important Himalayan rivers, e.g. the Kosi, Ghagra and Gandak. The study will be useful to design engineers, flood forecasting authorities, power generation, etc.

Keywords: *Himalayan rivers, Ganga river basin, Rainfall, Floods*

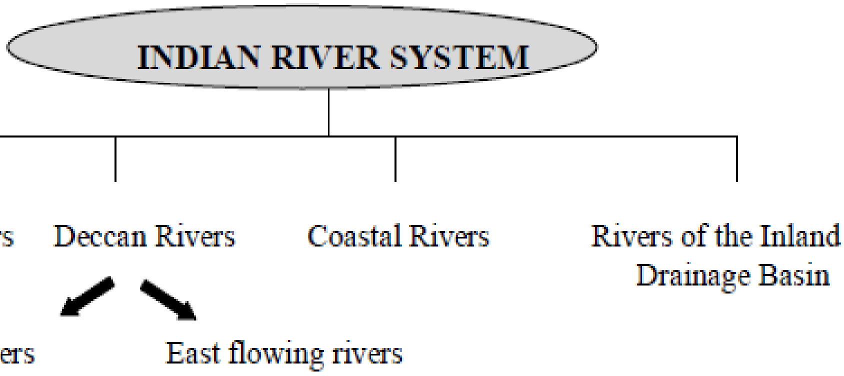
INTRODUCTION

Floods have been occurring from time immemorial. It may be said that ever since monsoon activity started in this part of the world, floods have been occurring regularly every year. Over the global scenario, floods are common events in South Asia. In fact, it has been said that after Bangladesh, India is the worst flood affected country in the world (Agarwal and Narayan, 1991) and about one fifth of global death occurs due to floods. Therefore, it is essential to have the knowledge about the magnitude and frequency of floods experienced by rivers for flood forecasting, proper design of water resources projects viz. dams, culverts, highways, etc. The frequency with which such damage may occur must be considered in determining the size or strength of the structure, its location, or the feasibility of building it at all. Besides, flood frequency analysis indicates the catchment characteristics, water availability and possible extreme hydrological conditions at various locations of any river system. This is very much essential from country's economy point of view and to overcome human loss and property.

India is one of the top five countries of the world (Brazil, Canada, Congo, India and Russia), having enough water resources. Nature has been kind to give this country a four to five months long monsoon period and moreover the orographic features of India are responsible for causing heavy rainfall which ultimately results in flooding of rivers and valleys during the monsoon months. Indian rivers constitute major share in the total water resources of the country. Seven major rivers (Indus, Ganga, Brahmaputra, Narmada & Tapi, Mahanadi, Godavari and Krishna) along with their numerous tributaries make up the river system of India.

The water discharge from India accounts for about 4.5% of global river discharge. A monthly discharge pattern of Indian rivers is the reflection of rainfall received maximum generally during July-August months. Some of the rivers draining eastern India also receive the northeast monsoon rains; their discharge pattern therefore shows the effect of these rains as well.

Relating to the climate, the frequent natural disaster experienced in India are droughts, flash floods, landslides, avalanches, cyclones, hurricanes and Tsunami. It is said that floods are the deadliest of natural disasters as all other disasters like landslides, avalanches and even hurricanes fall short when a heavy gush of water comes in a short time. It has a record of causing the maximum amount of damage in terms of life and property. World Resources Institute (WRI) developed a tool known as Aqueduct Global Flood Analyzer (AGFA) quantifies and visualizes the reality of global flood risk. WRI ranked 164 countries and found that the 15 countries account for nearly 80% of the total population affected every year. Among these, India ranks on the top (see Fig.1).



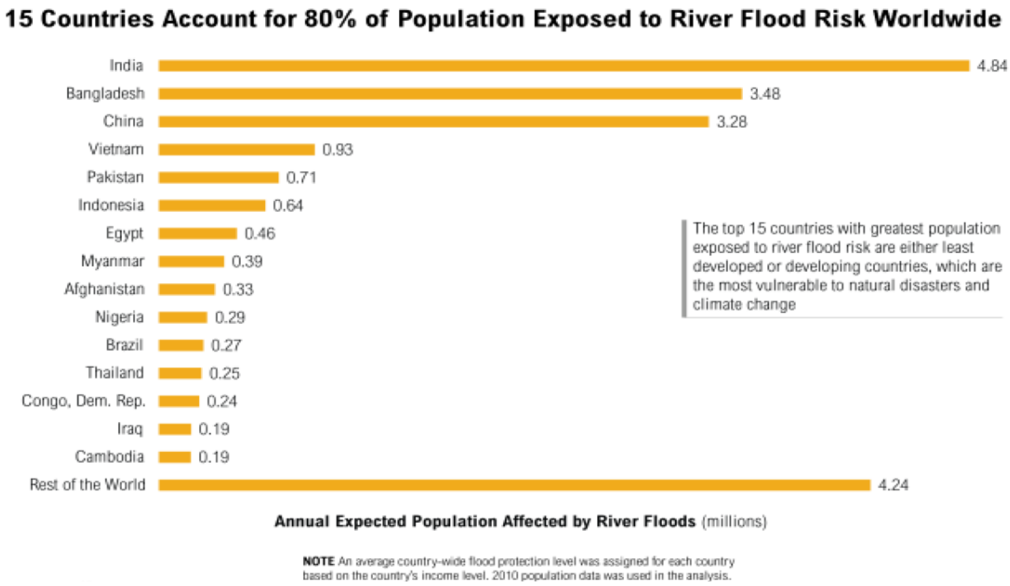


Figure 1. *Annual Expected Population affected by river floods (in millions)*

(Source: http://www.wri.org/)

Being hazardous to human life and wealth, countries economy; floods are studied by many more authors worldwide. In India, flood frequency analysis of different river basins has been carried out using different statistical distributions by many authors viz. Khan (2013) –Narmada river at Gurdeshwar site, Sathe et al (2012) – Upper Krishna river basin, Mukherjee (2013) - Subarnrekha river, Das and Kureshi (2014) – JiyaDhol river of Brahmaputra valley, Sah and Prasad (2015)- Kosi river, Guru and Jha (2015) - Tel basin of the Mahanadi river system, Kamal et al (2016). Flood disaster management studies are done by Nirupama (2015) and Tayal et al (2015) - Uttarakhand region. Bapalu and Sinha (2006) carried out flood hazard mapping study for the Kosi river. Flood management has been studied by Mavalankar and Srivastava (2008) for the Surat city and by Gupta et al (2012) for Leh (Ladakh).The above mentioned studies are mostly restricted to small sub-basins of the large rivers. Dhar and Nandargi (1989,1992,1993,1994,1995,1998,2000,2001a& b,2002,2003,2004a&b), Nandargi and Dhar (1996,1997,1998,2003a&b,2004,2008),Nandargi et al (2007, 2010) have carried out a number of flood studies of Indian rivers based on available rainfall and flood data to study different aspects of floods in different regions of India.

In the past thirty years, the country has experienced ten worst floods namely over Bihar (1987,2004,2008), Uttarakhand (2013), Jammu

& Kashmir (2014), Ladakh (2010), Assam (1998, 2012), Maharashtra (2005) and Chennai (2015). It is, therefore, clear that north India experience floods, more particularly, the regions falling in the sway of Ganga basin (see Fig.2) are more prone to severe or worst floods. According to a Central Water Commission (CWC) Report, nearly 37 million hectares (nearly 1/8th of India's geographical area) of fertile land are prone to floods at one time or another during the monsoon (Valdiya, 2004). Among the major Himalayan rivers, Ganga river system is the largest river system in the north India experiencing floods during every monsoon season. In view of this, the present study deals with the flood frequency analysis of the Ganga river and its major tributaries in the Indian region.

Morphological and Hydrological Characteristics of the Ganga Basin

The river Ganga is one of the three great rivers of the Indian sub-continent, viz. the Brahmaputra, Ganga and Indus. The Ganga drains the Indo-Gangetic plains of northern India between the Himalayas in the north and the Vindhya-Satpura mountain ranges in the south covering eleven states in north India (see Fig.2, Table 1). According to Rao (1975) the total catchment area of the Himalayan or northern tributaries of the Ganga is approximately 420000 sq.km while that of the southern tributaries, is 580000 sq.km extending over India, Nepal and Bangladesh. However, the northern tributaries of the Ganga, which originate in the Himalayas, contribute much more than the southern tributaries. Due to heavy precipitation over the Himalayas, especially during monsoon months, the normal annual runoff from the northern tributaries is about 25 times more than what it receives from the southern tributaries. The average annual flow of the Ganga at Farakka before entering into the Bangla Desh is 459,040 MCM (Rao, 1975).

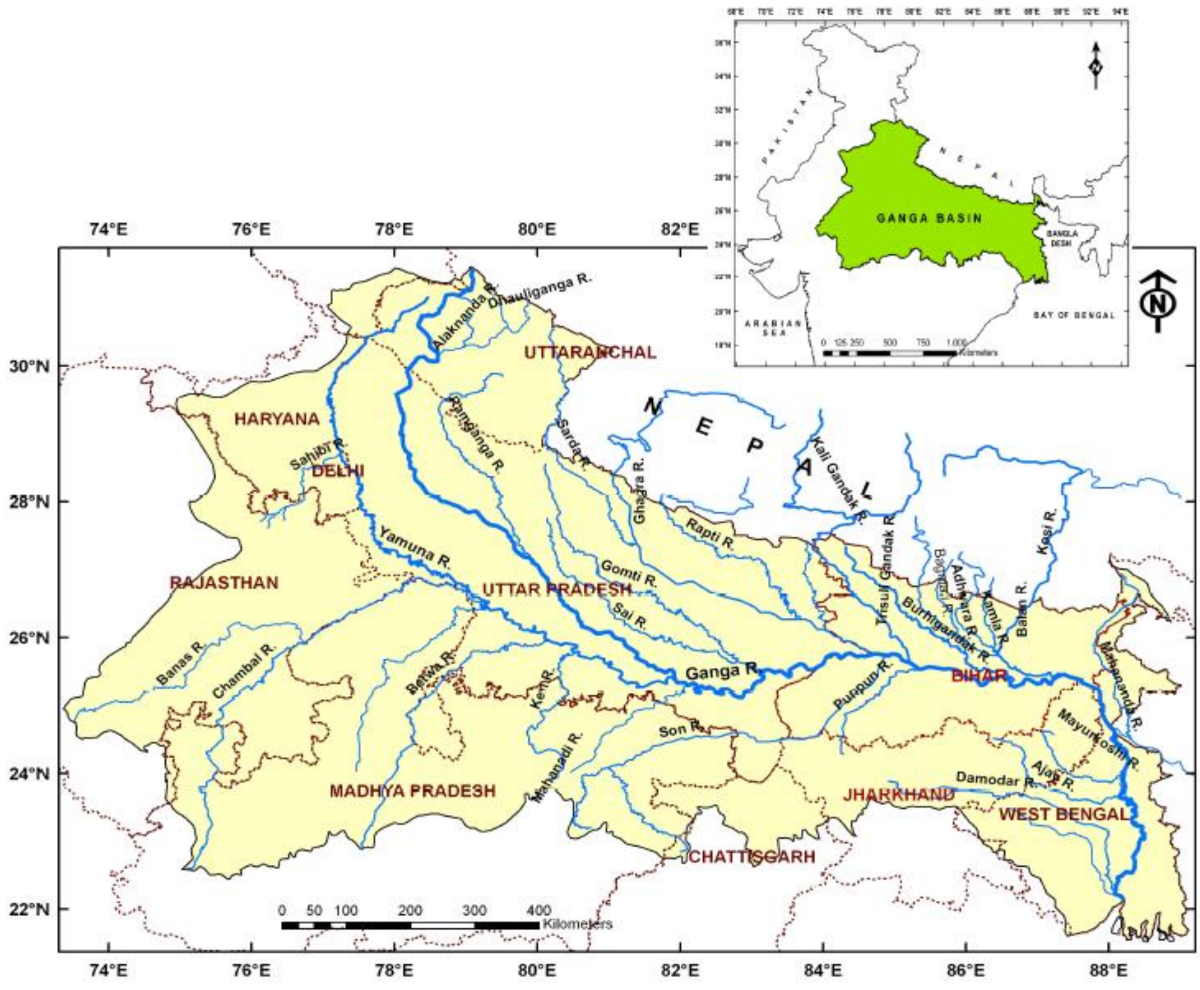


Figure 2. *Location map of Ganga basin showing states covered by the basin and its major tributaries*

The river originates from the Gangotri Glacier at Gomukh in the Garhwal Himalayas at an elevation of about 4100 m asl as named Bhagirathi. On the Bhagirathi river Tehri dam has been built in Uttarakhand for hydropower generation mostly for regulating the additional water discharge during the lean period. The Bhagirathi flows through the Himalayas and joins with the Mandakini and the Alaknanda at Dev Prayag, the point of confluence forming the upper reaches of Ganga. The combined stream is then known as the Ganga (Fig.2). Ganga enters the plain area at Haridwar, where a large quantity of water is diverted from this site into the Upper Ganga Canal, to provide water for irrigation. During the monsoon months, water gets diverted at two barrages one at Bijnor into the mid-Ganga and another at Narora into the Lower Ganga Canal. River Ramganga joins Ganga near Kannauj, and adds additional water to the river.

The northern tributaries of the Ganga are Ram Ganga, Gomati, Ghagra, Gandak and Sapt Kosi whereas Yamuna, Son, Punpun form the major southern tributaries (Fig.2). The rivers Damodar, Ajoy, Mayurkoshi join the Ganga river before it forms the deltaic region. The river after traversing a distance of 2525 kms from its source meets the Bay of Bengal at Ganga Sagar in West Bengal. Although the Yamuna originates from the Yamunotri glacier (at 6387 m) on the southwestern slopes of Lower Himalayas in Uttarakhand and is the westernmost longest tributary of the Ganga, it flows to the south and joins the Ganga at Allahabad (see Fig.2). Therefore, in this study, the Yamuna has not been considered as a northern tributary of the Ganga. As most of its tributaries flow into the Yamuna, to a large extent their flow originates from the western and central Indian region causing considerable flow between Allahabad (Uttar Pradesh) and Malda in West Bengal. The Farakka, end site on the Ganga river in West Bengal regulates the flow of the river and diverts some water into a feeder canal linking Hoogly to keep it relatively silt-free. Downstream of the Farakka site, Ganga river splits into two, Bhagirathi (Hoogly) on the right and Padma on the left. Bhagirathi (Hoogly) meets the Bay of Bengal about 150 km downstream of Kolkata. Padma enters into Bangladesh and meets river Brahmputra and Meghna before finally joining the Bay of Bengal.

Table 1. *Drainage area of the Ganga basin in different states*

States	Drainage area(km)
Uttarakhand and Uttar Pradesh	294364
Madhya Pradesh and Chhattisgarh	198962
Bihar and Jharkhand	143961
Rajasthan	112490
West Bengal	71485
Haryana	34341
Himachal Pradesh	4317
Delhi	1484
Total	**861404**

Topography of the basin

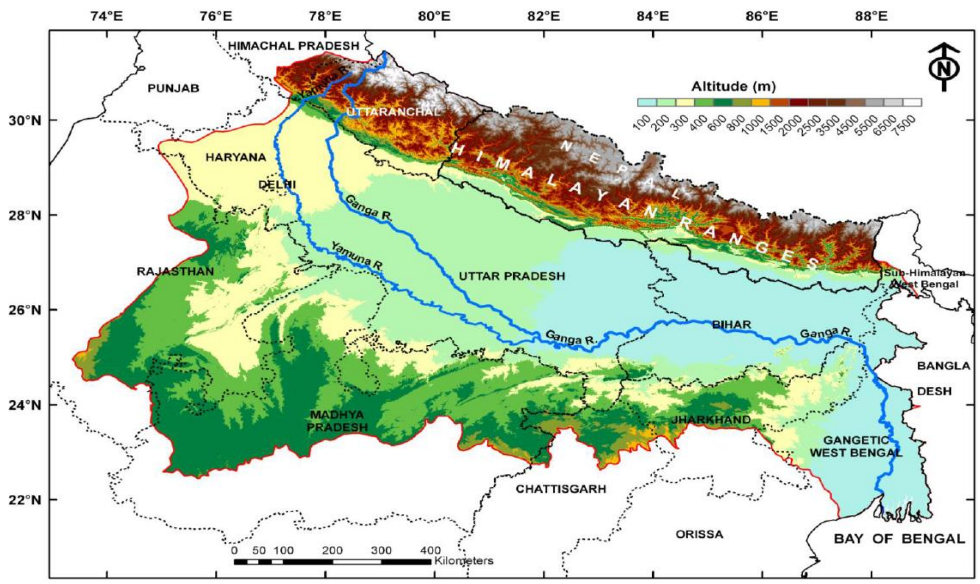


Figure 3.*Topographic features of the Ganga basin*

The topography of the Ganga basin plays major role in the water flow during flood situation and is characterized by an undulating terrain patterns. The highland region is situated on the northwestern and Northern portion of the basin in the form of Himalayan ranges (Fig.3). More than 58% of this region is covered by highly eroded mountain and submontane soil.

Maximum elevation is recorded about 7000 m in the north but where the Ganga river enters the Gangetic West Bengal, there elevation is even less than 100 m above the mean sea level. The plain region is situated on the south and south western part of the basin as isolated fluvial pockets. The altitude of this area is 100 to 800 m above the mean sea level. The Gangetic plain provides a huge receptacle into which thousands of meters of thick layers of sediments have been deposited to form a wide valley plain. (Ref. nmcg.nic.in).

Meteorological Situations Causing Heavy Precipitation In The Ganga Basin

- The Himalayas (especially its central and eastern sections) receive the bulk of its precipitation during two main seasons viz. winter months from November to March and the summer (southwest) monsoon months from June to September (or even up to mid-October). Heavy rain associated with monsoon depressions/ cyclonic storms or passage of quick succession of low pressure areas (LPAs) from the head Bay of Bengal in a northwesterly direction through the north Indian plains during the monsoon season cause the bulk of precipitation over the Himalayas especially when they are moving in a northwesterly direction and then recurve towards the north or northeast after traversing the plains of West Bengal, Orissa, Bihar and their neighbourhood. This results in intense flooding in the affected areas.

- Most of the winter precipitation is associated with the extra-tropical 'western disturbances' whose frequency per month during the winter varies from 3 to 5 on an average. These western disturbances are mid-latitude extra-tropical low pressure systems whose origin is somewhere around the Caspian Sea and these disturbances travel from west to east along the Himalayan latitudes after moving through Iran, Afghanistan and Pakistan during November through March. As these disturbances travel inland they encounter the Western Himalayas and its neighbouring lains where they contribute the bulk of the inter precipitation in the form of snow and rain.

- Floods are also caused in the Himalayan rivers by the setting in of 'break' situations in the monsoon. During the monsoon months, especially in the months of July and August, when the axis of the monsoon trough shifts from its normal position over the Indo-Gangetic plains to the foot-hills of the Himalayas, the 'Break' monsoon usually occurs. At this time the Himalayan region gets heavy to very heavy rainfall while the Indo-Gangetic plains to the south of the Himalayas do not experience any worthwhile rainfall. If active western disturbances also happen to move from west to east along the Himalayan latitudes, the synchronization of the two systems (tropical as well as extra tropical) can cause heavy rainfall (Dhar et al. 1982) and most of the Central and Eastern Himalayan tributaries are in high floods. This particular weather situation during the monsoon season occurs almost every year. e.g. in August 1954 well known widespread and devastating floods were caused by the Kosi in north Bihar by a weather situation similar to the one mentioned above (Dhar & Narayan, 1966).

It is clear that the weather situations mentioned above cause heavy precipitation over the Himalayas resulting in severe floods in the Himalayan tributaries of the Ganga basin. Unlike the peninsular rivers of India, these Himalayan rivers are perennial as they are also fed by the glacier and snow melt all through the year. Apart from the above main meteorological situations, the following factors also play an important role in augmenting floods in the river basins: -

- Indiscriminate destruction of forest and vegetal cover in the upper reaches of a river,

- Removal of vegetation from the hilly slopes or over grazing by the domestic animals,

- Deposition of silt washed down from bare and poorly covered hill slopes in the upper reaches of a river, Man-made obstructions to the free flow or rivers like bridges, embankments, etc.,

- Improper agricultural practices like shifting cultivation etc. and Failure of dams and artificial lakes created by advancing glacier tongues or land slides.

In fact, the Himalayas are now no longer the green wall that it used to be in good old days! These factors cause quick runoff from the steep hilly slopes and often flash floods are caused by the bursting of land-slides in downstream reaches. e.g. floods occurred in the Alaknanda

(1970), Bhagirathi (1978), Bagmati (1983), Kali (Sarda) rivers (1998). Recently in Jun 2013, Uttarakhand experienced the most disastrous flood event in the history of Indian floods. It was due to cloudburst followed by excessive and unprecedented rainfall for continuous 3-4 days in the hilly region of Uttarakhand resulting into flash floods and massive landslides in 9 districts. This ‘Himalayan Tsunami’ cost more than 5700 lives either dead or missing.In view of this, the present study deals with the different aspects of rainfall and floods experienced by the Ganga basin in India during 1986 to 2016.

Material And Methodology

Rainfall Data

India Meteorological Department (IMD) has divided the contiguous Indian area into 33 meteorologically homogeneous sub-divisions mostly on the basis of rainfall, temperature, orography, etc. Monthly, seasonal and annual rainfall data for 30 years (1986 to 2016) of 13 meteorological sub-divisions covering the Ganga basin is used to know the rainfall distribution over the basin.

Flood Data

In this country as stated earlier, there are about 53 major and medium river basins which generally get flooded during monsoon months of June to September. On each of these rivers there are one or more gauge/discharge (G/D) sites which record floods during the monsoon season. These sites are installed by State Governments in consultation with the Central Water Commission (CWC) which is the nodal agency for the development of water resources of India. These G/D sites on important flood-prone rivers are directly maintained and managed by the CWC for the issue of flood forecasts and warnings by the Central Flood Forecasting Organization and its sub-regional centers in flood-prone states. There are 23 G/D sites on the main Ganga river 33 G/D site on the northern tributaries and 31 G/D sites on the southern tributaries which record floods during the monsoon season (Fig.4). In the present study flood data recorded on these G/D sites for 1986 to 2016 have been considered for the analysis. Prior to 2004, the flood data were available on weekly basis from CWC, New Delhi through Weekly Flood News Letters (WFNL). Since 2007, flood data are available online on daily basis which gives a clear picture and water level position at different G/D sites on the rivers of the country. This helps in monitoring the high risk during the worst flood situations.

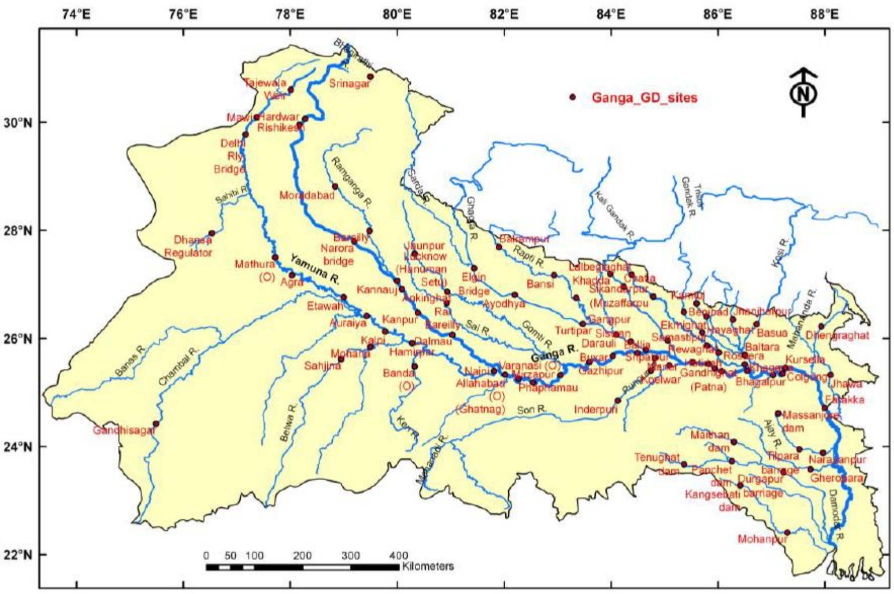


Figure 4.*Map of Ganga basin showing G/D sites on different rivers*

Methodology

Temporal and spatial distribution of rainfall over the Ganga basin on monthly, decadal and annual scale has been worked out along with its coefficient of variation over different sections of the basin to know the rainfall intensity in the Ganga river and its tributaries during the monsoon season using 1986-2016 rainfall data.

A flood is defined by various workers in different ways. According to Chow (1956), a flood is a relatively high stage of a river that overtakes the natural channel provided for its flow. According to Ward (1978), a flood is a body of water that rises to overflow land which is not normally submerged. In India, a river is said to be in flood when its water level crosses the danger level (DL) at that particular site. Major floods are those when water level is 1 m or more above the DL and if it is 5 m or more above the DL, that flood is said to be catastrophic.

In the present study, the frequency of floods (≥ 50) on different rivers and their respective G/D sites and highest deviation of flood from DL at different sites recorded during 30-year period (1986-2016) have been examined for the main Ganga river, its northern and southern tributaries. The highest flood level recorded during 1986-2016 was compared with the past highest flood level deviation to understand the intensity of floods in the basin.

Results and Discussion

Rainfall Distribution over the Ganga Basin

Normally monsoon sets in over the basin around last week of June and withdraws by the end of September or early October constituting only 70-75 days of the total monsoon period. The majority of the basin receives heavy rainfall in the months of July, August and September. Compared to western part, duration of monsoon rainfall is more over eastern part of the basin. Having a tropical climate, the basin receives annual average rainfall between 500 mm to 2500 mm, with an average of 1200 mm. More than 80% of the rainfall occurs during the monsoon months of June to September (Wet season) extending up to October. On an average, each square km of the Ganga basin receives a million cubic meters (MCM) of water in the form of rainfall. 30% of this is lost as evaporation, 20% seeps to the subsurface and the remaining 50% is available as surface runoff (Source: NGRBA, 2011).

There is lot of variation in the rainfall distribution over the basin. The lowest precipitation in the Gangetic plains occurs in Haryana (<500 mm/year) whereas in the Gangetic West Bengal, more than 1,500 mm/year of rainfall occurs (see Fig.5). Heavy to very heavy rainfall continues in the upper Himalayan region such as Himachal Pradesh, Uttaranchal, Sub-Himalayan West Bengal, e.g. Dehra Dun, receives rainfall as high as 2209 mm per year. Variability in the annual rainfall is in the range of 12 to 26% whereas for monsoon rainfall it is 14 to 30% indicating more variation in the monsoon rainfall. In the higher reaches of the basin, snow is also a significant part of precipitation. The winter precipitation that occurs in the form of snow in hilly areas accumulates until summer. During summer, there is considerable contribution from the melting of snow to the runoff.

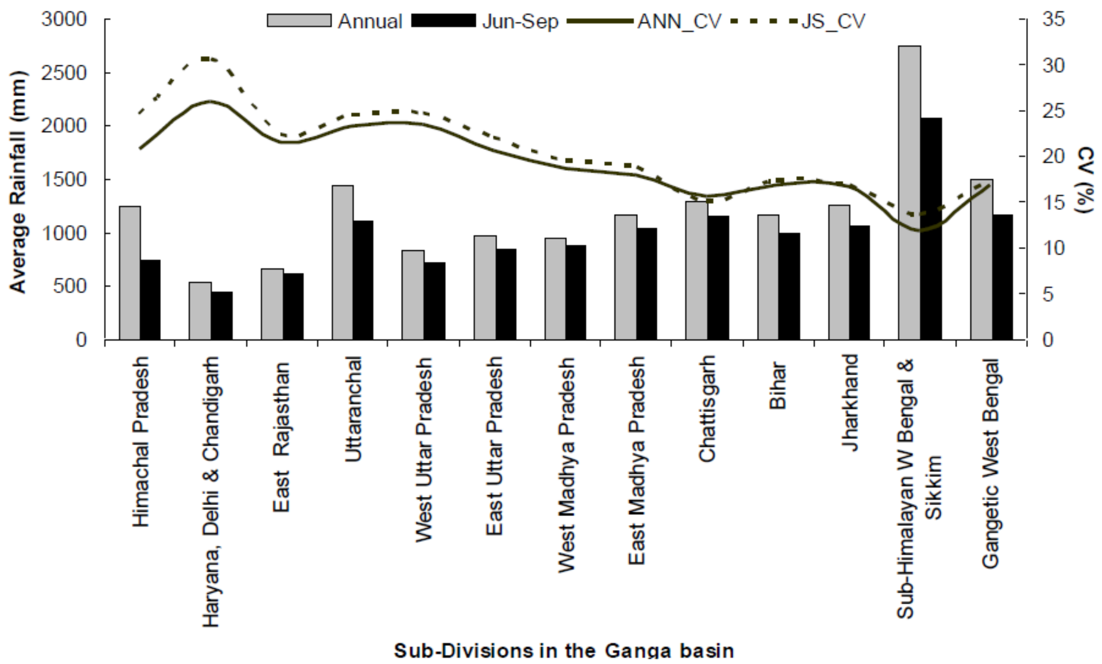


Figure 5. *Average seasonal (Jun-Sept) and annual rainfall with CV for sub-divisions in the Ganga basin (1951-2016)*

The yearly percentage departures from the long-term mean of Ganga basin rainfall and All India Monsoon (AIM) rainfall for the 13 sub-divisions for 1986 to 2016 (see Fig.6) showed that in most of the years Ganga basin rainfall is near equal or more than AIM rainfall. However, in the years, 1991, 1992, 1997, 1998, 2000, 2005, 2006, 2009, 2014, 2015 Ganga basin rainfall is less than AIM rainfall. The noteworthy decrease in rainfall in the years 1987, 2009, 2014 and 2015 is because country experienced severe drought conditions during these years.

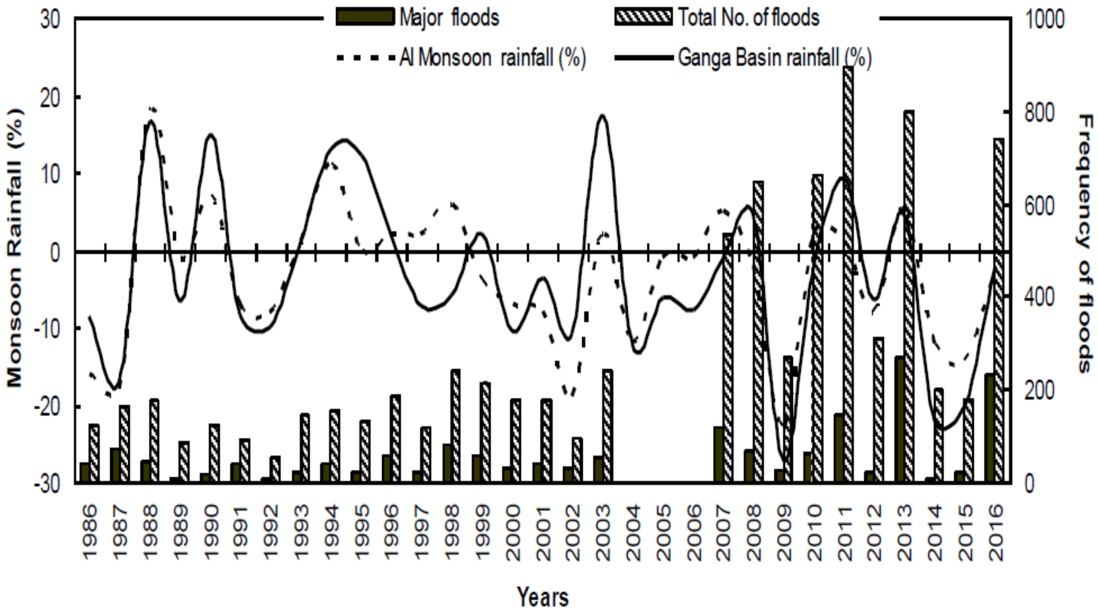


Figure 6.*Monsoon rainfall (All India & Ganga basin) and occurrence of total and major floods over the Ganga basin (1986-2004 weekly) and (2007-2016 daily)*

Floods in the Ganga River and its Major Tributaries

The number of occurrence of floods in the main Ganga river, its Himalayan (northern) tributaries, southern tributaries and tributaries joining before it falls in the Bay of Bengal is also examined for the period 1986 to 2016. It is to be recalled here that during 1986-2003 flood data was supplied on weekly basis and 2007 onwards daily flood data is available. Flood data for the years 2004 to 2006 is incomplete and hence not considered.

It is evident from Fig.6 that years of above normal monsoon rainfall can also produce a larger number of floods as happened in the years of 1988, 1998, 2003, 2008, 2010, 2011 and 2013. In deficient rainfall years like 1987, 1991, 1992, 2002, 2009, 2012, 2014 and 2015 there were floods at some G/D sites but their frequency was considerably low, except in the deficient year of 1987. Because of large temporal variations in precipitation over the year due to varied topography of the basin, there is wide fluctuation in the flow characteristics of the river. Monthly frequency of flood events showed (see Fig.7) that northern or Himalayan tributaries contribute more flow to the Ganga river than the southern tributaries. There are ten Himalayan rivers which contribute their flow into the main Ganga river after their confluence. August and September are the dominant months which contribute more to floods. This is mostly because monsoon sets in over this region in July. However; northern tributaries also experience floods due to melting of snow in non-monsoon months.

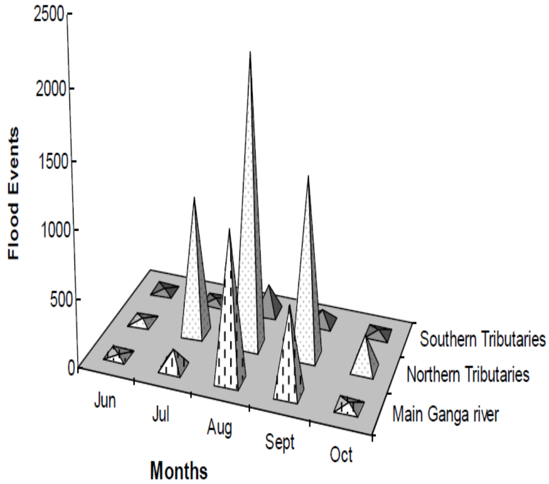


Figure 7.*Frequency of flood events in the main Ganga river and its tributaries*

The yearly frequency of floods at different G/D showed that the frequency of floods in the Himalayan tributaries has increased 1998 onwards (See Fig.8). The year 2011 recorded 566 flood events in the northern tributaries. However, there is substantial decrease in the drought years of 2009, 2012, 2014 and 2015.

The main Ganga river experienced more number of flood events in 1994, 1996, 1998, 1999 and 2003. In the years 1989, 2002 and 2009, the river recorded ≤ 10 flood events. It is also seen that the river experienced frequent floods due to excess rainfall during the 2013 monsoon season especially in the month of June.

Almost equal numbers of floods have been experienced by Ganga and its northern tributaries in 2013. Southern tributaries of the Ganga river experienced less number of floods in the years, 1989, 2001, 2002, 2003, 2011, 2016 this was mostly because of shifting of monsoon trough to south of its normal position causing heavy rainfall to central or peninsular India than over northern India. As stated earlier, floods were almost absent in the drought years 2007, 2008, 2009, 2012, 2014, 2015 (Fig.8).

During 1986 to 2003, frequency of major flood events (Section 4.3) is more in the Ganga river and its northern-southern tributaries compared to 2007 to 2016 period (see Fig.8). Years, 1996 and 2003 recorded higher number of major floods on the main river. 1987, 1998 and 1999 years recorded higher number of major floods on northern tributaries while during 2007-2016 frequency of major floods are highest in the year 2013 on the main Ganga river and 2007, 2011 and 2016 years recorded major floods on northern tributaries. Except the years, 1988, 1989, 1992 and 1998, southern tributaries recorded more flood events during 1986 to 2003 whereas 2016 recorded highest number of major floods (more than 80) in 2007 to 2016 period and there were no or very less number of major floods in the years 2014 and 2015.

The flood water gets accumulated from northern and southern tributaries of the Ganga river at different G/D sites.

The decadal frequency of floods at major G/D site on the Ganga river (Table 4) shows that Ballia, Colgong and Farakka sites experienced frequent floods in all the three decades with increase in frequency from one decade to another. Frequency of floods has increased in the recent decade of 2006 to 2016. This may be due to melting of snow in the northern tributaries of Ganga due to rise in temperature over the Himalayan region (Climate change impact), heavy rainfall due to long 'break' monsoon situation during the monsoon months of July and August. Decadal variation also shows that frequency of major flood events has also increased at all the three sites in all the three decades.

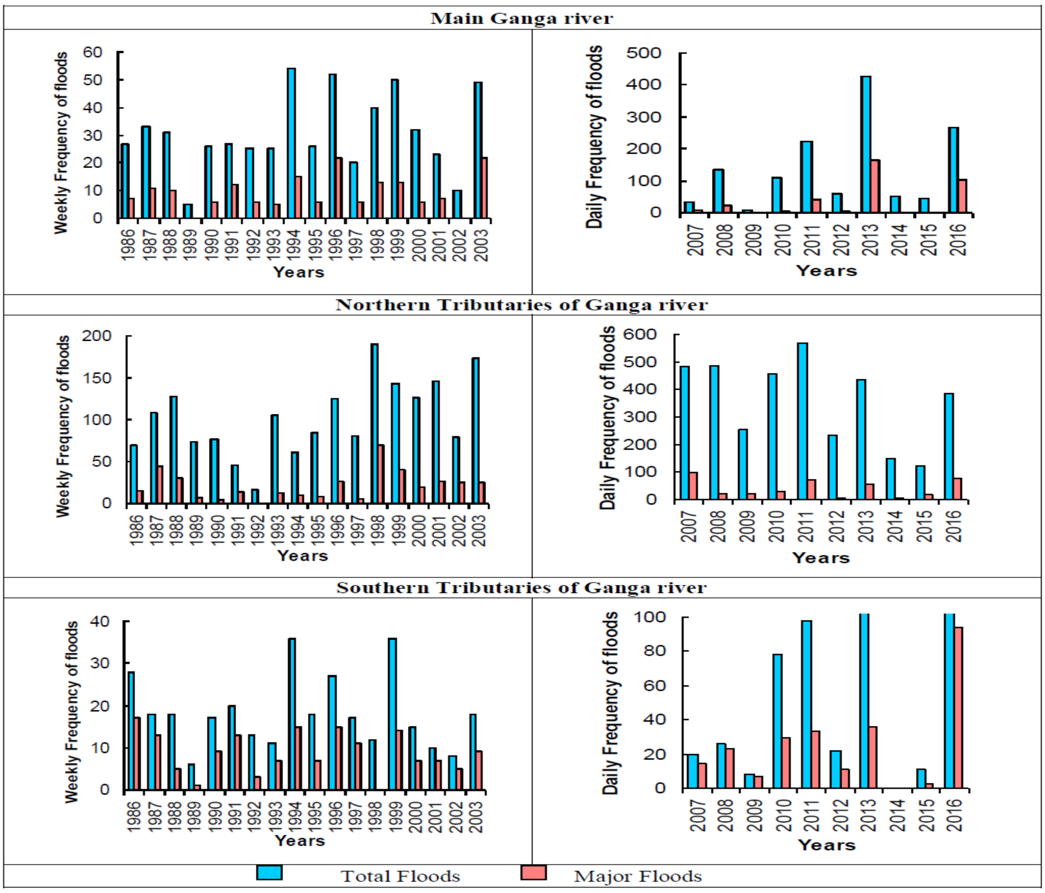
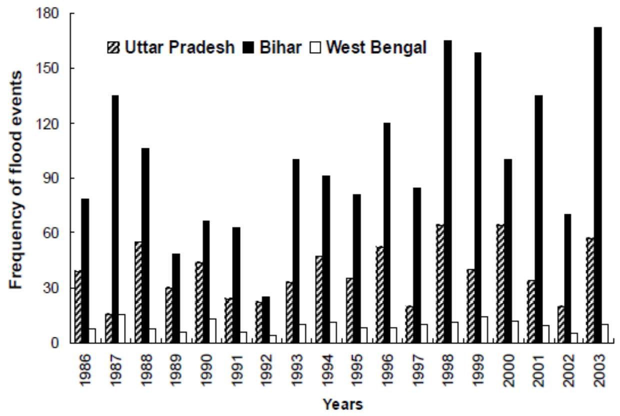


Figure 8. *Year wise frequency of floods in the Ganga river and its tributaries*

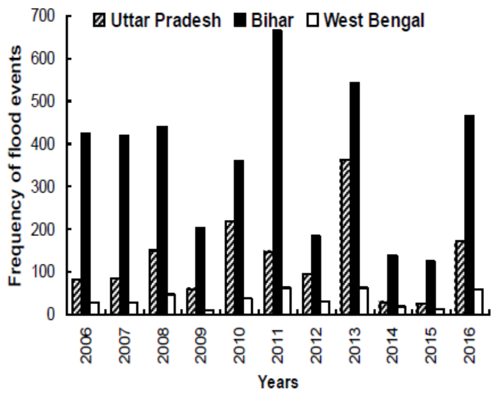
Table 4. *Decadal distribution of floods at different G/D sites of the Ganga river*

G/D sites at the main Ganga river	State	1986-1995		1996-2005		2006-2016	
		Tot	**M**	**Tot**	**M**	**Tot**	**M**
Hardwar	Uttar Pradesh.	8	2	12	3	17	5
Narora (Downstream)	"	2		2		2	
Ankinghat	"	1		2		11	
Dalmau	"	2		4		12	
Allahabad (Ghatnag)	"	2		3		15	4
Phaphamau	"	4	1	5	2	30	9
Mirzapur	"	3		4		19	4
Varanasi	"	6		8		36	10
Gazhipur	"	12	5	21	7	66	41
Ballia	"	46	22	80	34	155	85
Buxar	Bihar	7		12		52	4
Dighaghat (Patna)	"	10	2	16	2	51	9
Gandhighat (Patna)	"	36	4	65	8	212	40
Hatidah	"	25		44		159	18
Monghyr	"	4		5		32	
Bhagalpur	"	4		10		68	3
Colgong	"	40	8	80	18	270	51
Sahibganj	"					58	17
Farakka	West Bengal	68	33	137	70	430	160

State wise examination of flood frequency data for 1986-2003 and 2006 to 2016 showed that in the Ganga river basin, floods are most common in Uttar Pradesh, Bihar and Gangetic West Bengal (see Fig.9) which experienced highest flood events. Delhi and Haryana, Uttaranchal, Jharkhand experienced comparatively less number of flood events.



(Based on Weekly flood data)



(Based on Daily flood data)

Figure 9. *Frequency of flood events in three major flood experiencing states during a) 1986-2003 (weekly data) and b) 2006-2016 (Daily data)*

The frequency of floods at G/D sites in the Himalayan rivers is much less in the Uttar Pradesh region when compared to the Bihar region due to topography as in the hilly areas of Uttar Pradesh due to slope water flows rapidly to the plain areas like Bihar. Among the Himalayan rivers which flow through the Uttar Pradesh region, only the Ghagra at its three G/D sites, viz. Elgin Bridge, Ayodhya and Turtipar, experienced more than 250 floods whereas almost all the Himalayan rivers flowing through Bihar region experienced more than 200 floods during the last 31-year period.The highest numbers of floods were recorded at Baltara G/D site (>485) on the Kosi river. Benibad site on the Bagmati river, and the Basua and Kursella sites on the Kosi river recorded more than 300 floods.

Highest Flood Deviations Experienced At Different G/D Sites

Deviation in flood level from the normal D.L. at each G/D site on the main Ganga river and its

tributaries has been worked out for each year during 1986 to 2016. On the basis of the flood deviations, floods are categorized into three types – a) High floods (D.L. ≥1m), b) Very high floods (D.L. ≥ 2m) and c) Extreme floods (D.L. ≥ 4m).

Table 5. *Frequency of different types of floods at G/D sites*

No.	River	No. of times the G/D site experience		
		High Floods(≥1m)	Very Highfloods (≥2m)	Extremefloods (≥4m)
1	Main Ganga river	17	4	2
2	Northern tributaries (10)	23	12	1
3	Southern tributaries (7)	18	11	5

As shown in Table 5, 17 G/D sites on the main Ganga river recorded high floods. The frequency of high floods (i.e. ≥1m) is more on the Ballia (17), Colgong (11) and Farakka (23) G/D sites whereas frequency of very high floods is maximum (viz. 10) at the Farakka site and at Ballia it is 4. Extreme floods are recorded only at Ballia and Sahibganj site. The comparison of highest flood deviation recorded at each site on the Ganga river during 1986 to 2016 with the past highest ever deviation (see Fig.10) showed that 9 sites out of 23 sites viz. Haridwar, Fatehgarh, Kannauj, Ankinghat, Ballia, Gandhighat (Patna), Bhagalpur, Sahibganj and Farakka recorded highest deviations in flood levels crossing their previous records.

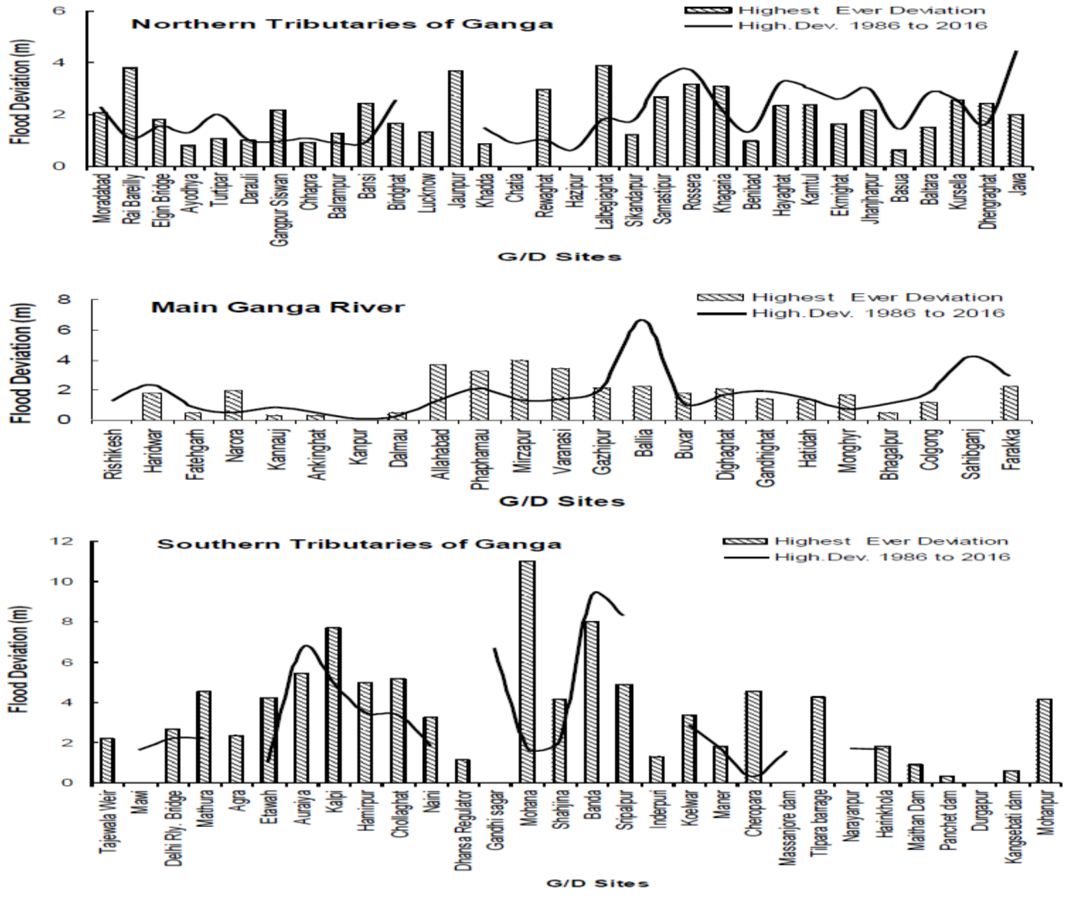


Figure 10. *Flood deviations (m) from the danger level (DL) at Gauge/Discharge sites on the Ganga river and its tributaries*

Ballia site recorded highest flood deviation of 6.64 m during 5-11 Sept.1996 and Sahibganj site recorded highest flood deviation of 4.21 m on 6 Sept. 1998.Among the northern tributaries of Ganga, Samastipur, Rossera and Khagaria (on Burhi Gandak river), Hayaghat (on Bagmati river), Kamtul (on Adhwara Group), Jhanjharpur (on Kamla Balan river), Blatara and Kursella (on Kosi river) G/D sites recorded more than 10 times high floods (≥1m), 12 sites on Ramganga, Ghagra, Burhi Gandak, Bagmati, Adhwara Group, Kamla Balan, Kosi and Mahananda rivers recorded very high floods (D.L. ≥ 2m) and only one site recorded extreme flood (D.L. ≥ 4m) above their respective D.L. (see Fig.10). Jhanjharpur site on the Kamala Balan river experienced 11 very high floods during the 31 years' period. It was also seen that 15 G/D sites surpassed their previous record of flood deviation at their respective D.Ls. All these sites recorded flood deviations of 2.5 to 3.0 m above their respective danger levels (D.L.s) (see Fig.10). The Jawa site on the Mahananda river recorded the highest flood deviation of 4.45 m in August 1996. Next to it are Samastipur and Rossera sites on the Burhi Gandak river and Hayaghat site on the Bagmati river which recorded more than 3 m of flood deviation

In southern tributaries of Ganga, 18 sites recorded high floods, 11 sites very high floods and 5 sites recorded extreme floods during 1986-2016 (see Table 5). The Yamuna, the Ken and the Punpun river experienced more number of high floods at different G/D sites. The Banda site on the Ken river and Sripalpur site on the Punpun river recorded 14 and 24 high floods during the 31 years' period. Even frequency of very high floods at these two sites was also 11 and 18 respectively. The Auriya and Kalpi sites on the Yamuna river, Gandhi Sagar site on the Chambal river, Banda site on the Ken river, Sripalpur site on the Punpun river experienced extreme floods (see Fig.10). On 8 occasions Banda site on the Ken river recorded extreme floods i.e. more than 4m above its D.L. It can therefore, be said that since southern tributaries of Ganga flow through the plain area, experience good number of high to very high floods. As shown in Fig.10, only three sites Auriya, Banda, and Sripalpur on the Yamuna, Ken, Punpun rivers crossed their previous highest flood deviation record. It is to be noted that for those sites where previous record is not available are not shown in the figure as some of the sites are newly introduced during the study period. Similarly, for some sites highest deviations record is not avaiable.

Catalogue of Highest Floods in the Ganga River System

From the foregoing it is clear that the Ganga and its tributaries recorded very to very high floods in the past 30 years or so. The catalogue of highest floods recorded in the Ganga basin during 1986–2016 at 67 G/D sites during the monsoon months of June–September is given in Table 6. It is seen from this Table that in the month of Aug. 2013, four sites in Uttar Pradesh and one site in Bihar recorded highest deviation in the flood level on the main Ganga river during the study period. Similarly, five sites on the Ganga river in Bihar plains recorded highest flood deviations in the 2016 year. This was mostly due to heavy to very heavy rainfall in the upper reaches of the Ganga river in the month of August. Of the 11 northern tributaries of the Ganga river, 25 sites recorded highest deviation in the flood level of more than 1m above their respective D.Ls. Again it is seen that 12 sites in the Bihar plain recorded highest flood deviations (≥2m) compared to 5 sites in the Uttar Pradesh state. 27 sites on 11 southern tributaries of Ganga showed highest flood deviations. The most affected rivers were the Yamuna and its tributaries, Chambal, Betwa and Ken in the Uttar Pradesh state and Punpun & Sone in the Bihar state. The smaller tributaries which join the Ganga river in the West Bengal also experienced high flood deviations.

Table 6. *List of highest recorded floods in the Ganga river and its tributaries*

Sr. No.	River	G/D site	State	Danger level (m)	Highest flood Deviation from D.L. (m)	Date & year of occurrence
			Main Ganga river			
1	Ganga	Rishikesh	Uttarakhand	340.50	1.22	05.09.1995
		Hardwar	Uttarakhand	294.00	2.30	19.09.2010
		Allahabad (Ghatnag)	Uttar Pradesh	84.73	1.31	26.08.2013
		Phaphamau	Uttar Pradesh	84.73	2.09	26.08.2013
		Mirzapur	Uttar Pradesh	77.72	1.33	27-28.08.2013
		Varanasi	Uttar Pradesh	71.26	1.37	27-29.08.2013
		Gazhipur	Uttar Pradesh	63.11	2.03	01.09.1982
		Ballia	Uttar Pradesh	57.62	6.64	05 to 11.09.1996
		Buxar	Bihar	60.32	1.12	29-30.08.2013
		Dighaghat (Patna)	Bihar	50.45	1.67	21.08.2016
		Gandhighat (Patna)	Bihar	48.60	1.88	21.08.2016
		Hatidah	Bihar	41.76	1.41	22.08.2016
		Bhagalpur	Bihar	33.68	1.04	26.08.2016
		Colgong	Bihar	31.09	1.74	06.09.1998
		Sahibganj	Jharkhand	27.25	4.21	1998
		Farakka	West Bengal	22.25	2.89	07.09.1998
	Northern Tributaries of Ganga (from west to east)					

2	Ramganga	Moradabad	West U.P.	190.60	2.28	21.09.2010
3	Sai	Rai Bareilly	Rai bareilly	101.00	3.81	17.09.1982
4	Ghagra	Elgin Bridge	Uttar Pradesh	106.07	1.81	1950
		Ayodhya	Uttar Pradesh	92.73	1.28	11.10.2009
		Turtipar	Uttar Pradesh	64.01	1.99	28.08.1998
		Gangpur Siswan	Uttar Pradesh	57.04	2.17	17.08.1980
		Chhapra	Bihar	53.68	1.07	11.08.1988
5	Rapti	Birdghat (Gorakhpur)	Uttar Pradesh	74.98	2.56	23.08.1998
6	Gandak	Khadda	Uttar Pradesh	96.00	1.50	23.07.2002
		Rewaghat	Uttar Pradesh	54.41	2.97	01.08.1977
7	Burhi Gandak	Lalbegiaghat	Bihar	63.20	3.81	02.08.1975
		Muzaffarpur (Sikandarpur)	Bihar	52.53	1.76	15.08.1987
		Samastipur	Bihar	46.02	3.36	15.08.1987
		Rossera	Bihar	42.63	3.72	16.08.1987
		Khagaria	Bihar	36.58	3.08	19.08.1978
8	Bagmati	Benibad	Bihar	48.68	1.33	12.07.2004
		Hayaghat	Bihar	45.72	3.24	14.08.1987
9	Adhwara Group	Kamtul	Bihar	50.00	2.99	12.08.1987
		Ekmighat	Bihar	46.94	2.58	12.07.2004
10	Kamala Balan	Jhanjharpur	Bihar	50.00	3.01	10.07.2004
11	Kosi	Basua	Bihar	47.75	1.42	25.08.2010
		Baltara	Bihar	33.85	2.81	20.07.1998
		Kursella	Bihar	30.00	2.55	10.07.1980
12	Mahananda	Dhengraghat	Bihar	35.65	2.44	15.08.1968
		Jawa	Bihar	31.40	4.45	15-21.08.1996

Table 6.contd….

Sr. No.	River	G/D site	State	Danger level(m)	Highest flood Deviation from D.L. (m)	Date & year of occurrence
Southern Tributaries of Ganga						
13	Yamuna	Tajewala Weir	Haryana	323.70	4.57	03.09.1978
		Mawi	Delhi	230.85	1.60	26.09.1988
		Delhi Rly Bridge	Delhi	204.83	2.67	06.09.1978
		Mathura	Uttar Pradesh	165.20	4.53	08.09.1978
		Agra	Uttar Pradesh	152.40	2.36	09.09.1978
		Etawah	Uttar Pradesh	121.92	4.21	11.09.1978
		Auraiya	Uttar Pradesh	113.00	5.19	25.08.1996
		Auraiya	Uttar Pradesh	110.00*	6.63	30.07.1986
		Kalpi	Uttar Pradesh	108.00	4.98	25.08.1996
		Kalpi	Uttar Pradesh	105.00*	7.70	27.08.1982
		Hamirpur	Uttar Pradesh	103.63	4.96	12.09.1983
		Chillaghat	Uttar Pradesh	100.00	5.16	06.09.1978
		Naini	Uttar Pradesh	84.74	3.25	08.09.1978
14	Sahibi	Dhansa Regulator	Delhi	212.44	1.14	06.08.1977
15	Chambal	Gandhi Sagar	Rajasthan	399.90	6.70	02.06.2005
16	Betwa	Mohana	Uttar Pradesh	122.66	11.03	11.09.1983
		Sahjina	Uttar Pradesh	104.54	4.13	12.09.1983
17	Ken	Banda	Uttar Pradesh	104.00	9.29	07.07.2005
18	Punpun	Sripalpur	Bihar	50.60	8.27	07.09.2001
19	Sone	Koelwar	Bihar	55.52	3.36	20.07.1971
		Maner	Bihar	52.00	1.79	10.09.1976
20	Ajoy	Gheropara	West Bengal	39.42	4.52	27.09.1978
21	Mayurkoshi	Massanjore dam	West Bengal	121.31	1.56	25.09.1999
		Tilpara barrage	West Bengal	62.79	4.26	27.09.1978
		Narayanpur	West Bengal	27.99	1.70	27.09.1995
22	Mundeshwari	Harinkhola	West Bengal	12.80	1.78	29.09.1978
23	Kangsebati	Mohanpur	West Bengal	25.73	4.14	02.09.1978

*Note: * D.L. on these sites changed in 1996. Therefore, change in D.Ls. prior to 1996 and after 1995 are mentioned in the Table.*

Compared to northern tributaries deviation in the flood level in the southern tributaries is higher i.e. more than 3 m above their respective D.L. on 16 G/D sites. The most severe among these were Mohana site on Betwa river, Banda site on Ken river and Sripalpur site on the Punpun river which recorded highest deviations in the flood level of 11.03 m, 9.29 m and 8.27 m respectively.Table 7 gives the list of G/D sites which experienced floods for 20 years or more during the study period. It is seen from Table 7 that, four sites on the Ganga river, 13 sites on the northern tributaries and only one site on the southern tributary of the Ganga river experienced flood almost every year. It was also observed that the Gaga at Farakka, Ghagra at Turtipar, Kamla Balan at Jhanjharpur and Kosi at Baltara experienced floods during every monsoon season. The Baltara G/D site on the Kosi river has experienced 486 flood events and 177 major floods (Table 7) compared to other sites. Therefore, it appears to be the most flood-affected site as far as the Himalayan rivers of the Ganga are concerned.

Table 7. *List of G/D sites which experienced flood every year (1986-2016)*

River Name	G/D site	No. of Flood years	No. of Flood events(Major floods)
Ganga	Ballia	21	155 (85)
	Hatidah	20	159 (18)
	Colgong	26	268 (51)
	Farakka	28	430 (160)
Northern Tributaries :			
Ghagra	Elgin Bridge	27	325 (12)
	Ayodhya	27	278 (12)
	Turtipar	28	277 (7)
	Gangpur Siswan	21	129 (0)
Burhi Gandak	Khagaria	25	215 (68)
Bagmati	Benibad	25	382 (8)
Adhwara Group	Kamtul	24	193 (12)
Kamla Balan	Jhanjharpur	29	199 (60)
Kosi	Basua	25	346 (6)
	Baltara	27	486 (177)
	Kursella	26	309 (69)
Mahananda	Dhengraghat	26	207 (21)
	Jawa	26	150 (18)
Southern Tributaries :			
Punpun	Sripalpur	26	193 (142)

Daily Deviation in the Flood Level at the Farakka end Site on the Ganga River

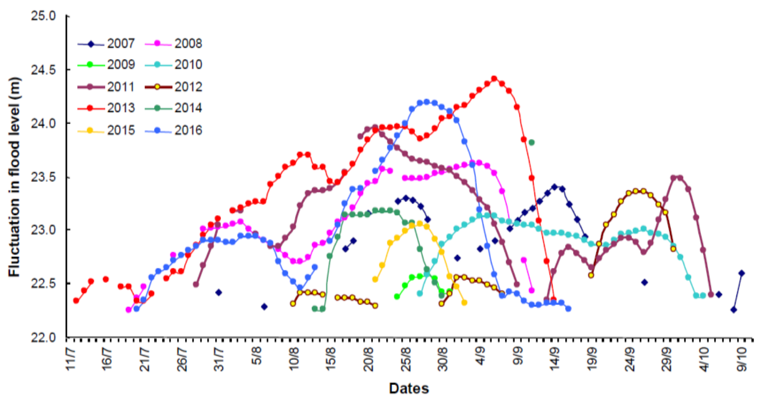


Figure 11. *Daily fluctuation in flood level at Farakka G/D site during 2007-2016*

Farakka is second site on the main Ganga river experiencing more than 400 flood events with 160 major floods during the study period. However, percentage (74%) of experiencing major floods (≥1 m) above the D.L. is highest at the Sripalpur site on the Punpun river. In this connection it may be mentioned that at an old G/D site on the Kosi in Nepal Terai at

Barakkshetra, the flood deviation from D.L. was 7.14 m on 24 August, 1954 which corresponded with a peak discharge of 2.4 x 106 m3sec-1 (i.e. 8.55 x 105 cusecs) (Dhar and Narayan, 1966). In another devastating flood in the Kosi, the deviation was 11.29 m above the D.L. at Barakkshetra site on 5 October, 1968 (Rao, 1975).Efforts are also made to examine the daily variation in the flood level during the monsoon seasons of 2007 to 2016 at the end site, Farakka on the Ganga river (see Fig11). It is seen from Fig.11 that Farakka site as mentioned earlier experienced peak floods in the 2013 and 2016 years in the last week of August to first week of September. Heavy floods get accumulated at this site during the third week of August to second week of September. The number of days the site experienced flood above the D.L. during this period showed that during the drought years of 2009, 2012, 2014 and 2015 the site was above the D.L. for 8, 29, 20 and 21 days respectively.

Discussion

The Ganga basin is one of the largest river basins in the north to northwest region of India, i.e. Bihar, Uttar Pradesh, Himachal Pradesh, Delhi and Haryana and neighbourhood. Since, the region is located in the foot hills of the Himalayas is the area of highest rainfall in India. The main meteorological situations that cause heavy to very heavy rainfall over the Ganga basin are due to the shifting of the seasonal monsoon trough to the foothills of Himalayas in the north and 'Break' monsoon situations along with the movement of tropical disturbances in the northerly to northeasterly direction during the monsoon season. The mean annual rainfall over this region is of the order of 500 mm to 2500 mm with a high co-efficient of variability, this being of the order of 14–30% during the monsoon season. Examination of rainfall and flood data for the period 1986 to 2016 showed that among all the Himalayan rivers joining the Ganga from the north, the major contributions come from the Kosi, Ghagra and Gandak and their tributaries joining the Ganga along its course through Gangetic plains. This bulk of water along with heavy silt load causes flooding in the main Ganga during the monsoon months in the States of east Uttar Pradesh, Bihar and West Bengal (Fig.9). It was seen that these states experienced floods every year. Noteworthy decrease in frequency was recorded in the years 1992, 2009, 2012, 2014, 2015 due to severe drought condition all over the country as no major rainfall producing systems formed over the sea or over the land. Whereas maximum flood events recorded during the years 1987, 1998, 1999, 2001, 2003, 2013 having experienced good monsoon rainfall.

The long period flood records show that 50% G/D sites out of 57 whose flood records of highest deviation have not been surpassed so far. About 26 G/D sites, recorded flood deviations more than 3m above their respective D.Ls. In India up to 1997, about 30 G/D sites over 17 rivers recorded catastrophic floods (Dhar and Nandargi, 1998). Ballia site on Ganga river, Auriya, Kalpi, Hamirpur, Chillaghat sites on Yamuna river, Gandhisagar on Chambal river, Mohana and Banda on Betwa river and Sripalpur site on Punpun river recorded catastrophic floods of more than 5m above their respective DL. However, so far, the highest deviations from DL are considered, on the Teesta river (in northeast India) it was of the order of 18.10 m on the 4 October 1968 at the Anderson Bridge G/D site and 17.87 m on the Narmada River at G/D site, Garudeshwar on 6 September 1970 (Dhar and Nandargi, 1998).

Conclusion

Climate change is a greater driver of change in population exposure to river floods than socioeconomic development, because both the frequency and intensity of river floods is expected to increase due to climate change in many areas making no difference between developed and under developing countries (World Bank Report No.8, 2008) This phenomenon would expand flood-prone areas, and make floods more likely to occur in those areas more often. By 2030, river floods could affect 2 million more people, and 70% of that increase will be due to climate change. Since all these Himalayan rivers are perennial in nature due to their source being in glaciers and ice caps, the harnessing of the waters of the main important Himalayan rivers viz. Ganga and its northern tributaries is essential in progress and prosperity of the respected states. Therefore, to utilize this enormous volume of flood water from the Himalayan rivers, it is suggested that multi-purpose water resources projects should be undertaken to conserve the flood waters and utilize them for agriculture, industry and hydro-power generation during the lean dry months. This can be achieved only by building multi-purpose dams across these rivers within the Himalayas or at suitable sites where they debouch into the plains. A good number of such sites are also available especially in the Karnali river in Nepal. In this respect the full cooperation and participation of the Nepal Government with the neighbouring Indian States is considered to be essential. In connection with this, it is worth mentioning what Khosla (1958), one of India's top engineers, said some 60 years back: *"Floods are an evil in so far as they cause destruction to life and property but floods are potential resources and blessings. This resource can be wasted harmlessly to the sea by suitable engineering works, but of really vital importance is the utilization of these surplus flood waters for purpose of irrigation, power development, navigation, etc. Such utilization can be achieved by conserving the flood supplies in for beneficial use, and thereby eliminating the death and destruction."*

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AUTHORS CONTRIBUTION

The concept of the study, literature review, accumulation of rainfall, analysis and interpretation of results, drafting of the manuscript and its critical revision was performed by the authors.

CONFLICTS OF INTEREST

There is no conflict of interest.

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