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Climate change impact, mitigation and adaptation strategies for agricultural and water resources, in Ganga Plain (India)

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Abstract Agriculture consumes more than two-thirds of global fresh water out of which 90 % is used by developing countries. Freshwater consumption worldwide is expected to rise another 25 %by 2030 due to increase in population from 6.6 billion currently to about 8 billion by 2030 and over 9 billion by 2050. Worldwide climate change and variability are affecting water resources and agricultural production and in India Ganga Plain region is one of them. Hydro-climatic changes are very prominent in all the regions of Ganga Plain. Climate change and variability impacts are further drying the semi-arid areas and may cause serious problem of water and food scarcity for about 250 million people of the area. About 80 million ha out of total 141 million ha net cultivated area of India is rainfed, which contributes approximately 44 % of total food production has been severely affected by climate change. Further changing climatic conditions are causing prominent hydrological variations like change in drainage density, river morphology (tectonic control) & geometry, water quality and precipitation. Majority of the river channels seen today in the Ganga Plain has migrated from their historic positions. Large scale changes in land use and land cover pattern, cropping pattern, drainage pattern and over exploitation of water resources are modifying the hydrological cycle in Ganga basin. The frequency of floods and drought and its intensity has increased manifold. Ganga Plain rivers has changed their course with time and the regional hydrological conditions shows full control over the rates and processes by which environments geomorphically evolve. Approximately 47 % of total irrigated area of the country is located in Ganga Plain, which is severely affected by changing climatic conditions. In long run climate change will affect the quantity and quality of the crops and the crop yield is going to be down. This will increase the already high food inflation in the country. The warmer atmospheric temperatures and drought conditions will increase soil salinization, desertification and drying-up of aquifer, while flooding conditions will escalate soil erosion, soil degradation and sedimentation. The aim of this study is to understand the impact of different hydrological changes due to climatic conditions and come up with easily and economically feasible solutions effective in addressing the problem of water and food scarcity in future.

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1 Introduction

Earth's history shows that in the past earth climate changed due to natural reasons, like Milankovitch effects, Plate tectonics and rise of mountain chains (Ruddiman 2001). But the present reason of climate change is the increase concentration of carbon dioxide in the atmosphere (IPCC 2007). The Intergovernmental Panel on Climate Change (IPCC) in 2001 has also indicated that the global climate is changing, largely because of human activities (Mitchell et al. 2001). Since the beginning of the 20th century drastic changes have been recorded in surface temperature, precipitation, evaporation and extreme events like floods, droughts and cyclone. In the 20th century, 1990s was the warmest decade and 1998 was the warmest year and one of the major causes of this global warming was the emission of greenhouse gases due to anthropogenic activities (Houghton et al. 2001). The changes in the climate will trigger long-term and potentially extensive, changes in the hydrological cycle, with significant impacts on society and on the environment (Arnell et al. 2001). Figure 1 shows the effect of greenhouse gases and global warming on the hydrologic cycle. World-wide there is consensus among the researchers and the scientists that global climate instability may occur if the current rate of greenhouse gas (GHG) emissions continues. The frequency of drought and floods has increased worldwide manifold. Agriculture consumes more than two-thirds of global fresh water out of which approximately 90 % is used by developing countries (Statistical Yearbook for Asia and the Pacific 2007). Freshwater consumption worldwide has more than doubled since World War II and is expected to rise another 25 % by 2030 (Wild et al. 2007). Majority of the growth is because of the increases in the world population from 6.6 billion currently to about 8 billion by 2030 and over 9 billion by 2050 (Morrison et al. 2009). Thus our future depends how we are going to minimize the impact of climate change because it affects both agricultural production and fresh water resources.

1.1 Ganga Plain

Ganga plain is considered as an active peripheral foreland basin of Himalaya and is subjected to compressional stress of the moving Indian plate, which has uplifted the Himalaya (Seeber et al. 1981; Burg and Chen 1984; Molnar 1984). The Ganga Plain occupies a central position in the Indo-Gangetic Plain. It extends from Aravalli-Delhi ridge in the west to the Rajmahal hills in the East, Himalayan foothills (Siwalik Hills) in the north to the Bundelkhand Vindhyan Plateau-Hazaribag plateau in the south. It is located within the states of Bihar, Uttar Pradesh and Uttaranchal in India, approximately between latitude 24°N and 30°N. The total length of the Ganga Plain is approximately 1,000 km, its width ranges between 450 and 200 km and occupies an area of about 250,000 km^2. The river systems within Ganga plain shows evidence of preferential alignment, asymmetrical terrace building (Singh et al. 1996). Rivers in Ganga Plain have shifted their courses with time and are responsible for the variations in their channel geometries, which modify the landforms. According to Lyon-Caen and Molnar (1985) Ganga Plain has been formed due to elastic flexing of the Indian Plate under part load of the Himalaya. Pathak in 1982 divided the Ganga Plain in four geomorphic unit i.e. Bhabar, Terai, Central alluvial plain and marginal alluvial plain. The central alluvial plain occupies the maximum area, in the Ganga Plain and is the part of Ganga basin, while the Marginal alluvial plain occupies the smaller area and belongs to Yamuna basin.

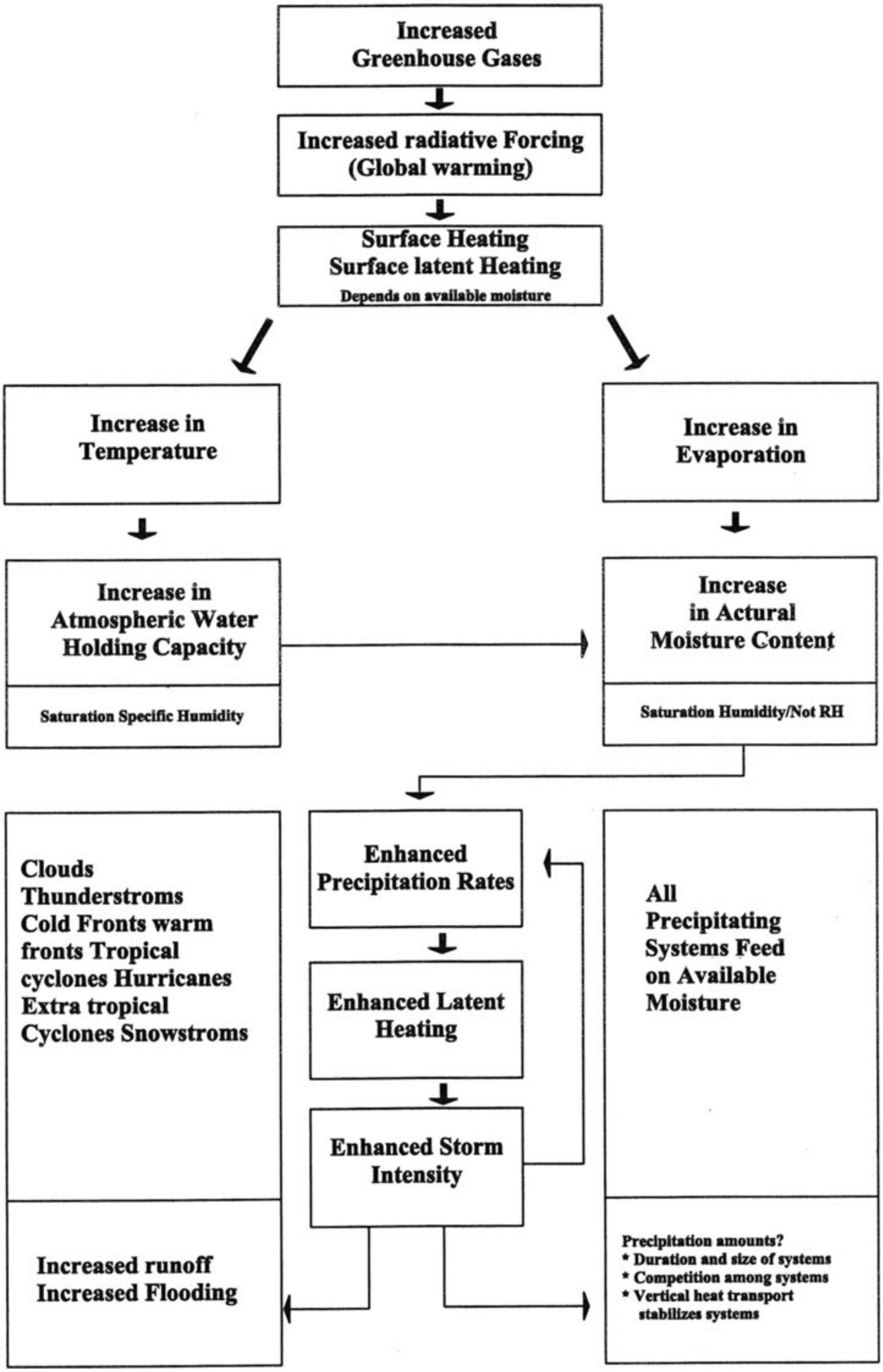

Fig. 1 Conceptual model of climate change and variability impacts on the hydrologic cycle (Trenberth 1999)

The majority of India's population is rural and agriculturally oriented and they depend on rivers and groundwater. Groundwater is the major source for fulfilling the domestic demand of more than 80 % of rural and 50 % of urban population, besides fulfilling the irrigation needs of around 50 % of irrigated agriculture. It has been estimated that 70 to 80 % of the value of irrigated production in India comes from groundwater. (Mall et al. 2006). Contribution of groundwater to India's Gross Domestic Product (GDP) has been estimated at about 9 % (Burjia and Romani 2003). The enhanced human activities driving the climate change has manifest effects on groundwater systems, including groundwater storage, recharge and discharge rates are evident in recent times. In India the average food consumption at present is 550 g per capita per day. The major challenges for the country is to increase its food production to 300mt by 2020 in order to feed its ever growing population, which is likely to reach 1.30 billion by the year 2020. To meet the demand for food from its increasing population the country's farmers need to produce 50 % more grain by 2020 (GOI 2003). It seems to be very difficult to fulfill the increasing food demand because climate warming is causing serious problems like soil salinity, soil erosion, desertification and depletion of water resources in Ganga Plain as well as other parts of the country. If necessary and effective actions were not taken in time, then in near future food production is going to be down sharply. It will increase food inflation manifold. Further global warming is also escalating hydrological variation in different parts of region. The continuous increasing variations in drainage density, river geometry and morphology, water quality, and precipitations have shown serious impact on ground water quality, water table position, precipitation and hydrogeology. The objective of this study is to understand the impact of different hydrological changes due to climatic warming and come up with solutions effective in addressing the water and food scarcity problems.

2 River geometry of Ganga Plain

The rivers of the Ganga Plain play an important role in the lives of the people in the region. The river systems are providing water for irrigational, domestic and industrial purposes, as well as generating electricity, and the livelihoods of a large number of people are depend upon them. This is the major reason, why nearly all the major cities of the Ganga basin are located in the banks of rivers. Figure 2 shows the area of the Ganga basin and different river systems. The migration of river within the Indo-Gangetic Plain is one of the serious environmental problem (Singh and Sontakke 2002), which is affecting the hydrology of the region. Between 1731 and 1963, the course of the Kosi River (the sorrow of Bihar) has shifted westward by about 125 km; courses of Ganga, Ghaghara and Son at their confluence have shifted by 35 to 50 km since the epic period68 (~1000 BC) and that of the Indus and its tributaries by 10–30 km in 1,200 years in the same direction (Wilhelmy 1967). Between 2500 BC and AD 500 the course of the Yamuna river shifted westward to join the Indus and then east to join the Ganga thrice (Raikes 1968).

The western part of the Ganga Plain is occupied by the Marginal alluvial Plain, which is the north-sloping surface. This zone comprises of the alluvial sediments brought down by northerly flowing rivers originating from the plateau region. The sediment thickness in marginal alluvial plain varies between 60 and 200 m. Yamuna, Chambal, Betwa, Ken, Tons and Sindh are the major rivers of the marginal alluvial Plain. The total catchment area of the river is 3,63,848 sq.km of which 1,39,468 sq.km is the drainage area of Chambal alone. The state wise catchment area is given in Table 1. Most of the meandering rivers are coming from the southern plateau areas flow in NE direction. The rivers draining the gangetic plains exhibit remarkable geomorphic diversity and this has consequently characterized the rivers to be dominantly aggradational in the eastern gangetic plains (Shina 2005). The rivers

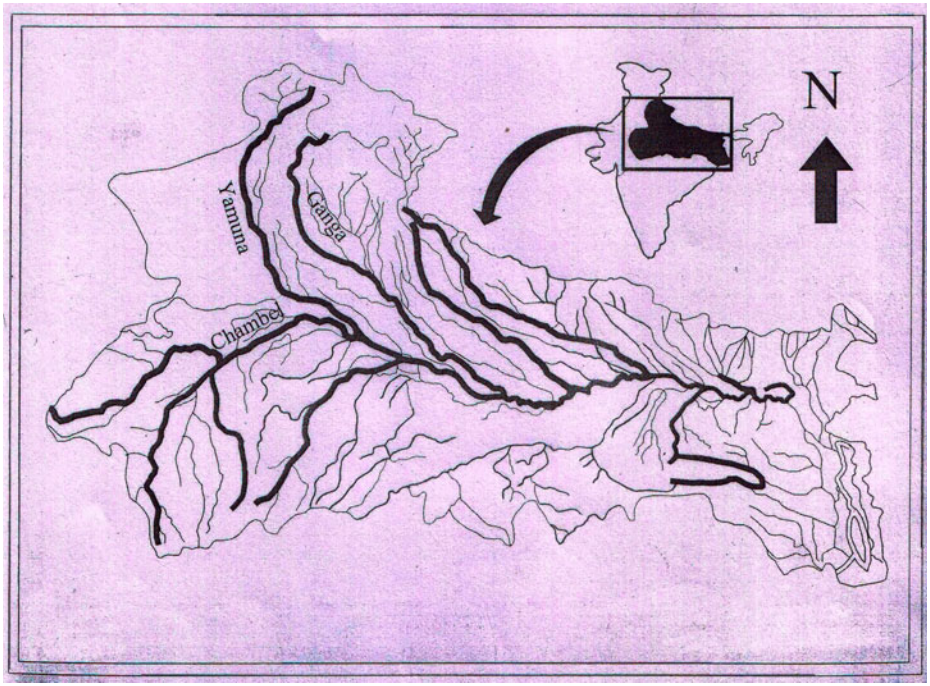

Fig. 2 Showing the location of Ganga basin and different river systems (after Misra 2011)

drained the gangetic plain plays a very important role in the supply of water for irrigational, industrial and domestic purposes for large population of about 250 million people of the region. The geomorphic diversity across the Ganga Plains manifested as variability of fluvial processes and spatial distribution of different geomorphic elements (Shina et al. 2005). Ganga Plain rivers drain through a distinct rainfall gradient across their eastern western extent. Western parts receive less rainfall (from 60 to 140 cm) in comparison to eastern parts (90–>160 cm) both in the hinterland and alluvial plains (Singh 1994). The Northern part of the Ganga plain receives more rainfall as compare to the Southern part and the amount and distribution of rainfall in space and in time directly control the discharge variability in rivers throughout the year but particularly during the monsoon months (Shina 2005). Table 2 shows different hydrological characteristics of the rivers in Ganga Plain.

Table 1 Yamuna sub-basin and state wise catchment area in sq.km. (Source: Shiva and Jalees 2003)

State	Total catchment area
Uttar Pradesh including Uttranchal	74,208
Himachal Pradesh	5,799
Haryana	21,265
Rajasthan	1,20,883
Madhya Pradesh	1,40,208
Delhi	1,485
Total	3,63,848

Table 2 Hydrological characteristics of the rivers in Ganga Plain. (Source: Jain and Sinha 2003)

River	River type	Total basin area (10^3 km^2)	Average annual discharge (cumecs)	Average sediment load (mt/year)	Discharge per unit area (cumecs/km^2) *10^{-3}	Sediment yield (10^3 t/year/km^2)	Source
Ganga (Haridwar)	Mountain-fed	95	757	14	8	0.15	Abbas and Subramanian 1984.
Ganga (Kannau)	Mountain-fed	240	1252	15	5	0.06	Abbas and Subramanian 1984.
Yamuna	Mountain-fed	366	2949	125	8	0.34	Abbas and Subramanian 1984.
Ramganga	Mountain-fed	32	482	10	15	0.31	Abbas and Subramanian 1984.
Gomti	Plains-fed	30	235	6	8	0.20	Abbas and Subramanian 1984.
Rapti	Foothills-fed	20	–	15.6	–	0.78	Chandra 1993
Ghaghra	Mountain-fed	127	2993	125	24	0.98	Abbas and Subramanian 1984.
Gandak	Mountain-fed	43	1555	82	36	1.91	Sinha and Frien; 1994
Burhi Gandak	Plains-fed	10	273	15	27	1.50	Sinha and Friend 1994
Baghmati	Foothills-fed	8	189	7	23	0.87	GFCC 1991
Kamla-Balan	Mixed -fed	3	68	8	23	2.67	Sinha and Friend 1994
Kosi	Mountain-fed	95	1792	193	19	2.03	NIH 1993
Ganga (Farakka)	Mountain-fed	648	14555	729	22	1.125	Abbas and Subramanian 1984.

The Ganga basin is also one of the highly cultivated lands in the country. Its cultivatable land covers approximately 509,994 sq.km, consisting almost 62.5 % of the total area of basin. It contributes to about 37 % of the total population of the country, of which about 84 %in rural areas and 16 % live in towns and cities. Ganga river is no longer only a source of water but is also a channel receiving and transporting urban wastes away from the towns. Approximately, one third of the country's urban population lives in the towns of Ganga basin. Out of the 2,300 towns in the country 692 are located in the basin and of these 100 are located along river bank itself (Sharma 1997). In Central alluvial plain there are seven important tributaries feeding the Ganga from the North and six joining from the South and five joining the river in the last reaches of the Hooghly. Ganga receives over 60 % of its discharge from its tributaries. Human-induced changes to river channels and their tributaries have greatly modified the streamflow characteristics in the Ganga Plain. The processes of channelizing or straightening a river by dredging can more efficiently pass flood discharges through the straightened segment, but the faster water velocity can erode more sediment. Therefore restricting a stream within artificial embankments, such as floodwalls, prevents it from naturally meandering, but can create new problems. Thus any type of human modifications to river geometry and floodplains should be carried out after detail study of physical, hydrological and ecological systems of the rivers.

3 Tectonic and river morphology

In low-relief and densely populated areas like Ganga plain the detection of possible tectonic activity is very difficult because very few applicable methods exist, especially if the area is characterized by low seismicity. It can be studied by geomorphic evaluation, such as analysis of river dynamics, which has been found to be an appropriate tool (Quchi 1985). Even the smallest change in the topography affects the sinuosity of low gradient rivers (Holbrook and Schumm 1999). Providing hints on on-going micro-topographic changes.

In Marginal and Central alluvial plain the rivers shows distinct morphology and regimes. Generally in alluvial plains the river flows between banks and on a bed composed of sediments that is deposited by river itself. Alluvial rivers are sensitive to changes in sediment load, water discharge and valley floor slope (Schumm 1977). Majority of rivers in both the plains carry good amount of silt load, due to this rivers flow being slower in both the plains. When the silt load becomes heavier, rivers start winding in these plains first cutting at the one bank and then eroding at the other. The meandering and the braided streams are most common morphological features of the rivers in marginal and central alluvial plain. The distinct river morphological features of marginal and central alluvial plain are shown in Table 3. The analysis of linear structural elements and lineament trends of rivers and in other parts of marginal and central alluvial plain was carried out with the help of remotely sensed data. Figures 3 and 4 and Tables 4 and 5 represents the lineament trends of the rivers in both the plains. In alluvial plains rivers tend to evolve as single meandering channels, when influenced by tectonic movements. This process is largely independent of river side especially in Ganga Plain. Most of the river channels seen today in the Ganga Plain have been migrated from their historic positions. The course of the rivers in Ganga plain has been changed with time (Sarkar et al. 2003) due to: (i) subsurface geotectonic movement leading to change in slope of the deltatic plain and subsidence of the Bengal basin (ii) Changing pattern of water discharge with time (iii) variation in sediment load.

Generally the pattern of seasonal flow of water in any river is called its regime. The river regime in marginal and central alluvial plain is distinct. The major differences in the flow

Table 3 Morphological characteristics of the marginal and alluvial rivers of the Ganga Plain

Key features of marginal & central alluvial plain	
Marginal alluvial plain	Central alluvial plain
1. Low drainage density	1. High drainage density
2. Shifting or migration of rivers is observed	2. Shifting or migration of rivers is high in nature
3. Small meander loops, only sinuous nature is visible.	3. Large meanders with high sinuosity and bank erosion.
4. Narrow flood plain	4. Broad flood plain
5. Yamuna forms the axial river	5. Ganga is the axial river
6. Gully erosion forming ravines	6. Ravines are rare
7. All rivers are originating from Vindhyan craton.	7. All Rivers are originating from Himalaya/Ground water fed.
8. Main structural domain is Aravali & Vindhyan.	8. Main structural domain is Himalaya.

pattern of the rivers originating in the Himalayas from those of other rivers are in fact caused by differences in climate. The Himalayan Rivers and the groundwater fed/Perennial rivers and their regimes are dependent on the pattern of water supply both from snowmelt and rainfall. The regimes of the Himalayan Rivers are monsoonal as well as glacial, while the regimes of the groundwater fed/perennial rivers are only monsoonal as they are controlled by rainfall alone. Majority of the rivers in Central alluvial plain originates from the Himalaya

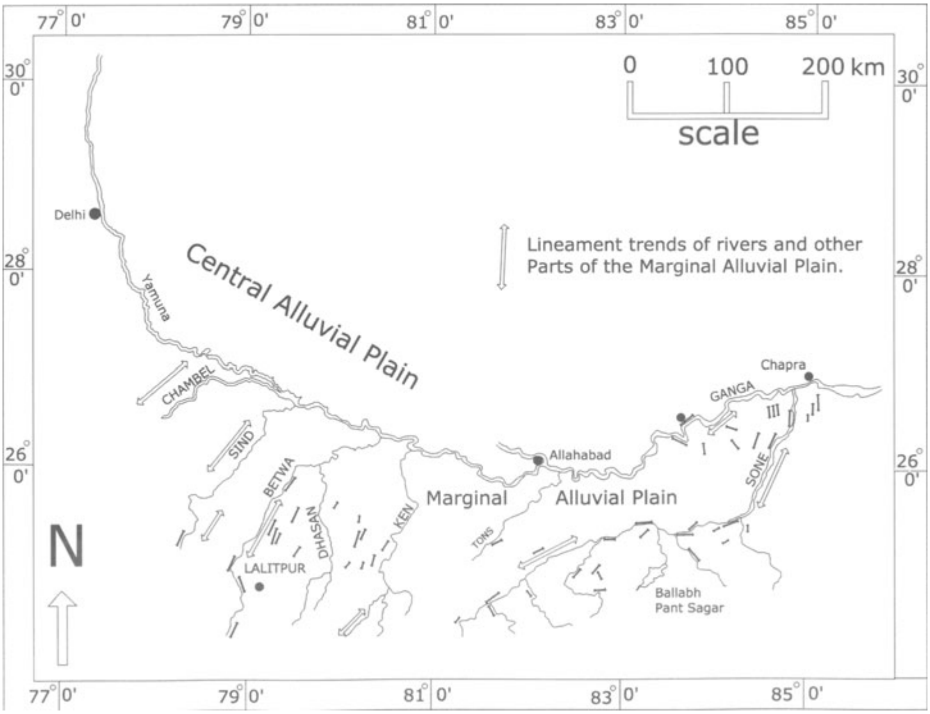

Fig. 3 River morphology in marginal alluvial plain (source: Singh et al. 1996)

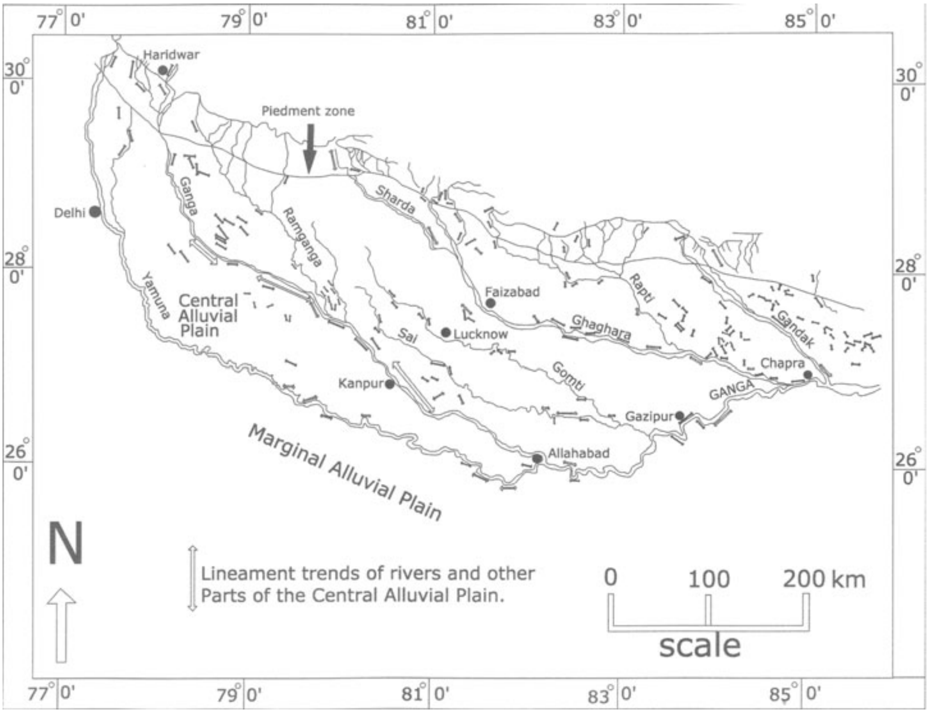

Fig. 4 River morphology in central alluvial plain (source: Singh et al. 1996)

(e.g., Yamuna, Ganga, Ramganga, Rapti, Gandak) while the rivers of the Marginal alluvial plain are groundwater-fed. The marginal alluvial plain rivers have a very low volume of discharge from January to June, which suddenly rises in August and September, when the rainfall is maximum. The fall in the river discharge in October is as spectacular as the rise in August and September. The two major rivers such as Yamuna and Ganga originate from Yamunotri (Badarpunch, 6,316 m) and Gangotri (Chankhambh peaks, 7,138 m) glaciers. These differences in river regimes of the rivers of central and marginal alluvial plains are one of the main reasons of water scarcity and quality problems in the marginal alluvial plain.

Table 4 Lineament trend of the rivers in marginal alluvial plain (source: Singh et al. 1996)

Lineament trends of river in marginal alluvial plains	
Marginal alluvial plain	Major lineament directions
Chambal river	NW-SE
Sind river	SSW-NNE & WSW-ENE
Betwa river	SW-NE & SSW-NNE
Dhasan river	SW-NE & SSW-NNE
Ken river	WSW-ENE & SSW-NNE
Tons river	SW-NE
Sone river	SSW-NNE & WSW-ENE

Table 5 Lineament trend of the rivers in central alluvial plain (source: Singh et al. 1996)

Lineament trends of river in central alluvial plains	
Central alluvial plain	Major lineament directions
Yamuna river	NE-SW & NW-SE, WNW-ESE
Ganga river	NNE-SSW, NW-SE, NNW-SSE, NW-SE
Ghaghra river	NW-SE, NNE-SSW, NW-SE, NNE-SSW
Rapti river	NNW-SSE, WNW-ESE, WNW-ESE, NNE-SSW
Gomti river	NNE-SSW & NE-SW, WNW-ESE
Sai river	NNW-SSE & NW-SE

4 Impact of climate change and variability on water resources and agriculture

The impact of climate change and variability on water resources and agriculture will be one of the major deciding factors influencing future water and food security of the world including India. The climate varies naturally and the problem of climate change is not the greenhouse effect. The current change in climate results from enhanced greenhouse effects (Baede et al. 2001) caused by an increase in atmospheric concentration of anthropogenic trace gases. Further vegetation cover, land surface texture or roughness affects atmospheric dynamics through its influence on winds; mountains can also have large effects on the climate at regional and continental scale (Wang et al. 2004). Studies shows that the global mean sea level has risen by 10 to 20 cm and the frequency of severe flood in large river basins has increased during the 20th century (Milly et al. 2002).

In India studies carried out by different workers reveals that there is increasing trends in surface temperature (Rupa Kumar et al. 1994; Hingane et al. 1985). Large to small scale changes have been observed in evaporation, surface temperature, rainfall and the intensity and frequency of the water related hazards like floods and drought has been increased manifold. The summer monsoon rainfall over western Indo-Gangetic plains shows increasing trend (170 mm/100-year, significant at 1 % level) from 1900 and there has been a westward shift in rainfall activities over the Indo-Gangetic plains (Singh and Sontakke 2002). Nearly 40 million hectare of India is flood prone and every year 8 million hectares of land is affected by floods (IITM 1994). These changes on climatic condition have shown their impact on the food production in India and the food security of the South Asia. Approximately 80 million hectares, out of the India' s net sown area of around 143 million hectares, lack irrigation facilities and, hence, totally rely on rain water for crop growth. According to Srinivasa Rao et al. 2009 the Indian rainfall pattern shows negative trends of rainfall in the eastern parts of Madhya Pradesh, Chhattisgarh, Jharkhand, Uttar Pradesh and Northeast India. Lal (2001) indicated that annual mean area-averaged surface warming over the Indian sub-continent is too likely to range between 3.5 and 5.5 °C by 2080s and Indian Council of Agricultural Research (ICAR), has predicted that medium-term climate change will reduce the crop yields at between 4.5 and 9 % by 2039.

Both marginal and central alluvial plains are the most fertile areas of Ganga Plain. These areas have a semi-arid to arid climate with an average monthly temperature varying from of 35° to 45 °C in summer and 15° to 32 °C in winter. The climate of the region is dominated by the summer monsoon (June to September). The entire year is however divided into four seasons: (i) Winter {January and February} (ii) Pre-monsoon or Hot weather season {March–May} (iii) Southwest or summer monsoon season {June–September} (iv) Post

Monsoon season {October–December}. The precipitation in both the central and marginal alluvial plains is from South-West monsoon. The precipitation in the marginal alluvial plain varies from 400 to 650 mm/year, while that in the central alluvial plain varies from 500 to 1,000 mm/year. Year to Year deviations in the weather and occurrence of climate anomalies/ extremes become common. Precipitation is the only source of recharge to groundwater, but in the central alluvial plain rivers and canal network provides a good recharge to these areas. Approximately 90 % demand of water for Industrial, Irrigational and domestic purposes are fulfilled by Groundwater. Further 99 districts, spread over 14 states were identified as drought prone in the country by central water commission (CWC 2002). Sinha Ray and Shewale (2001) studied rainfall data from 1875 to 1998, which shows percentage area the country effected by moderate and severe drought (Table 6) and probability of occurrence of drought (Table 7). Since climate change and agriculture are interrelated processes, thus with warming climatic conditions, massive changes in farming practices and increase demand, it will be difficult to fulfill the demand of food and water in near future in the country. As per the Government of India's national communications (NATCOM) report in 2004 the crop

Table 6 Drought years with percentage area of the country affected by drought (source: Sinha Ray and Shewale 2001)

Year	Area affected by drought (as percentage area)		
	Moderate drought	Severe drought	Total
1877	30.6	28.9	59.5
1891	22.4	0.3	22.7
1899	44.1	24.3	68.4
1901	19.3	10.7	30.0
1904	17.5	16.9	34.4
1905	25.2	12.0	37.2
1907	27.9	1.2	29.1
1911	13.0	15.4	28.4
1913	24.5	0.0	24.5
1915	18.8	3.4	22.2
1918	44.3	25.7	70.0
1920	35.7	2.3	38.0
1925	21.1	0.0	21.1
1939	17.8	10.7	28.5
1941	35.5	0.0	35.5
1951	35.1	0.0	35.1
1965	38.3	0.0	38.3
1966	35.4	0.0	35.4
1968	21.9	0.0	21.9
1972	36.6	3.8	40.4
1974	27.1	6.9	34.0
1979	33.0	1.8	34.8
1982	29.1	0.0	29.1
1985	25.6	16.7	42.3
1987	29.8	17.9	47.7

Table 7 Probability of the occurrence of drought in different regions of India (Sinha Ray and Shewale 2001)

Subdivision	Probability of occurrence	Probability of occurrence of two consecutive droughts	Probability of occurrence of more than two consecutive droughts
Andaman and Nicobar islands	13	2	0
Arunachal Pradesh	8	0	0
Assam and Meghalaya	2	0	0
Nagaland, Manipur, Mizoram and Tripura	10	3	0
Sub-Himalayan West Bengal	6	1	0
Gangetic West Bengal	2	0	0
Orissa	4	0	0
Bihar Plateau	4	0	0
Bihar Plains	9	0	0
East Uttar Pradesh	10	1	0
Plains of West Uttar Pradesh	8	0	0
Hills of west Uttar Pradesh	14	1	0
Haryana, Delhi and Chandigarh	17	3	0
Punjab	16	4	0
Himachal Pradesh	16	3	2
Jammu and Kashmir	21	6	2
West Rajasthan	25	6	0
East Rajasthan	16	2	0
West Madhya Pradesh	10	1	0
East Madhya Pradesh	6	1	0
Gujarat Region	21	2	1
Saurashtra and Kutch	23	3	1
Konkan and Goa	7	0	0
Madhya Maharashtra	7	1	0
Marathwada	15	1	0
Vidarbha	12	1	0
Coastal Andhra Pradesh	10	1	0
Telangana	13	2	0
Rayalaseema	18	1	0
Tamil Nadu and Pondicherry	8	0	0
Coastal Karnataka	3	0	0
North Interior Karanataka	6	1	0
South Interior Karanataka	6	0	0
Kerla	7	2	0
Lakshadweep	10	2	0

production can drop by 4–5 million tones, with even a 1 °C rise in temperature. It means in future food inflation is going to be higher, because about 47 % of the total irrigated area in India is located in the Ganga basin. Without some form of water control across the Ganga river basins, freshwater lakes and associated aquifers, local and regional water and food security would not be possible.

5 Hydrological variation and escalation

The hydrological characteristics of the Ganga Plain and surrounding areas have undergone substantial changes as result of extensive changing land use and land cover pattern, drainage pattern and crop patterns. Warming climatic conditions led problems like soil degradation due to increasing soil salinity and erosion, desertification have aggravated the situation. Frequent hydrological disasters like flood and drought, enhanced variation in rainfall and runoff patterns and sedimentation are some of the major factors, escalating the hydrological variations. The snow line and glacier boundaries are sensitive to changes in climatic conditions. Almost 67 % of the Glaciers in the Himalayan mountain ranges have retreated in the past decade (Ageta and Kadota 1992). Glacial melt is expected to increase under changed climatic conditions, which would lead to increased summer flows in Ganga Basins Rivers for few decades followed by a reduction in flow as the glaciers disappear (IPCC 1998). Due to this majority of the perennials river of Ganga basin may become seasonal rivers and it may seriously affect the water and agricultural sector, on which human settlements and survival are depend. Thus both water resources and agricultural production are going to deplete against the increasing demand.

There is sharp decline in the quality of water both in the surface and groundwater due to increasing level of pollution from urban and industrial areas. Problems such as high concentration of salinity, fluoride, and nitrate in groundwater are escalating at fast rate and hydrological variation could be one of the contributing factors. Studies shows that the variability in the physical and chemical characteristics of groundwater can also occur on both vertical and horizontal dimensions on different scales and it is mainly due to separation by aquitards (Post 2003). It can also occur within a specific subaquifer due to smaller scale heterogeneity (Ronen et al. 1987). The physical variability with in aquifer is exhibited by large differences in hydraulic properties, which varies between aquifers, aquitards and aquicludes. These variabilities affect evaluation of both surface and groundwater resources, since many hydrological variables and parameters are uncertain in Ganga Plain. Further the variability in water salinity and chemistry is an important aspect in the area, which should be taken into account in describing the hydrological system. It has been revealed that the subsurface lithologies of the marginal and central alluvial plain exhibit distinctive features (Rao 1973; Sastri et al. 1971; Agarwal 1977; Qureshy et al. 1989). Numerous boreholes dug by Central Ground Water Board (CGWB) for water exploration also provide an insight into the nature of the alluvial succession of the Ganga Basin. The borehole information from 200 wells (100–750 m deep) of CGWB in different parts of the plain is summarized by Singh (1996). According to this the northern part of central alluvial plain shows about 5 % gravel, 45 % sand and 50 % mud, while its southern part shows 50 % mud-kankar, 20 % mud, 20 % sand and 10 % gravel. The marginal alluvial plain shows gravel-coarse sand 65 %, fine sand 10 %, mud kankar 25 %. These studies strongly support the view that there are large hydrogeological variations, which plays an important role in groundwater flow and quality.

Agriculture sector is the largest consumer of water resources in Ganga plain. About 80 % of the available water is used for agriculture alone. Since 1947 the irrigated area in India rose from 22.60 to 80.76 mha up to June 1997 (Mall et al. 2006). In India approximately 80 million ha out of 141 million ha net cultivated area is rainfed, which contributes to about 44 % of total food grain production of the country. Rainfed crops are likely to be severely affected by changing climatic conditions due to the limited options for coping with variability of rainfall and temperature. In marginal and central alluvial plains the aquifer recharge may be very uncertain when it has to be calculated. It does not only depend upon on the rate, which is variable spatially, and overtime and affected by land-use changes-but on the extent of the surface area, which is often unclear, especially when there are lateral inflows, and vertical inflows from other aquifers. Both marginal and central alluvial plains facing severe problems such as continuous groundwater-level decline, decrease of spring discharge or river flow, and also water quality changes which are assumed to be due to the displacement of groundwater in the aquifer system.

The problem of aquifer overexploitation of water resources is common. But it seems that in marginal alluvial plain, average aquifer abstraction rate is greater than or close to the average recharge rate, which is densely populated, and rainfall is scare than central alluvial plain. Moreover the progressive decrease in spring discharge, river base flow and surface area of wetlands in order to compensate for the difference between actual recharge and abstraction is more in marginal alluvial plain. It is believed that the groundwater flow pattern of Ganga plain has also been changed probably due to the tectonic and surface processes. This may favor the infiltration of contaminated surface water and the slow displacement of saline and poor quality groundwater bodies, some of them in deep seated aquifers and in aquitards. Poor quality water is affecting irrigated crops by causing accumulation of salts in the root zone by causing loss of permeability of the soil due to excess sodium or calcium leaching or by containing contaminants which are directly toxic to plants and indirectly to people of the region.

6 Discussion and conclusion

The United Nations Intergovernmental Panel on Climate Change fourth assessment report indicates that climate change and variability will have significant impact on crop production and water management systems in coming decades. In addition, there is the potential for earlier negative surprises linked to increased frequency of extreme events (Schmidhuber and Tubiello 2007). Since water resources are inextricably linked with climate, the prospect of global climate change and variability has serious implications for water resources and regional development (Houghton et al. 2001). The Ganga plain area contains the largest river system of India and is the major source of water and agricultural production in the country. Its climatic condition is controlled by the monsoon rains and is directly or indirectly connected to the tectonics and climate of Himalaya. Any changes in these factors are liable to adversely affect the hydrology, soil fertility, food production and settlement pattern of Indo Gangetic Plain. Further, its proximity to Thar desert is another cause of concern as the processes of sand movement can force undesirable modifications in the landscape under varying conditions of temperature and rainfall (Saini 2008).

Climate change and variability may have affected river morphology and geometry, water quality, and regional hydrology of the Ganga Plain. Impacts can be seen in the form of unprecedented heat waves, floods, drought, stalinization of the groundwater, soil salinity and decrease in snow cover, which is affecting snow-fed and glacial-fed rivers such as Yamuna, Ganga and their tributaries in the Ganga Plain. Approximately 65 to 70 % of the summer flow of these rivers comes from snow melt, which has been decreased and these rivers are losing water. Due to erratic climatic conditions drought and floods has become more common in the region, which has severely affected the agriculture sector. The crop yield per hectare has gone down and it has started showing its affect on food inflation.

The findings of the study demonstrated following points:

- The current water management practices in Ganga Plain are not capable to cope with the impacts of climate change on water availability, flood risk, health, agriculture, energy and ecosystems. Every year climate variability led flood and drought causes large damages and non-climatic factors, such as population growth are escalating these problems.
- The areas with arid and semi-arid climatic conditions especially western Indian states with prolonged dry seasons, rainfed crop production may carry a high risk of crop failure.
- The economical sustainability and performance of the country also depends on climate, as climate variability led drought and flood affects agricultural production, and agricultural has a large share in India's GDP.
- In India agriculture consume large amount of fresh water approximately 50 to 60 % of freshwater withdrawals go to irrigated farming. Increasing water scarcity and quality problems may decrease food production and supply, putting pressure on food prices and increase countries dependence on food imports.
- Occurrence of both droughts and flood at regional-scale or in large areas of country can be linked to the large-scale atmospheric circulation patterns over Ganga plain, which often occur simultaneously in different areas and severely affect the human activities.

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References

Abbas N, Subramanian V (1984) Erosion and sediment transport in the Ganges river basin (India). J Hydrol 69 (1–4):173–182

Agarwal RK (1977) Structure and tectonics of Indo-Gangetic Plains. Geophys Case Hist India AEG 1:29–46

Ageta Y, Kadota T (1992) Predictions of changes of glacier mass balance in the Nepal Himalaya and Tibetan Plateau: a case study of air temperature increase for three glaciers. Ann Glaciol 16:89–94

Arnell N, Liu C, Compagnucci R, Da Cunha L, Hanaki K, Howe C, Mailu G, Shiklomanov I, Stakhiv E (2001) Hydrology and water resources. In McCarthy JJ et al (eds) Climate change 2001: Impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, pp 192–234

Baede APM, Ahlonsou E, Ding Y, Schimel D (2001) The climate system: An overview. In: Houghton JT et al (eds) Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, pp 85–98

Burg JP, Chen GM (1984) Tectonic and structural zonation of southern Tibet, China. Nat London 331:219–223

Burjia JS, Romani S (2003) Indian J Public Adm XLIX:301–307

Chandra S (1993) Ph.D. Thesis (unpublished). University of Cambridge, Cambridge

CWC (2002) Water and related statistics. New Delhi. p 479

GFCC (1991) Unpublished report, Ministry of Water Resources, Government of India, Part II/9.

GOI (2003) Agricultural Statistics at a glance. Directorate of economics and statistics, Government of India, New Delhi

Hingane LS, Rupa Kumar K, Ramana Murthy BhV (1985) Long-term trends of surface air temperature in India. J Climatol 5:521–528

Holbrook J, Schumm SA (1999) Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing suitable epirogenic deformation in modern and ancient settings. Tectonophysics 305:287–306

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ (2001) The scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press UK, Cambridge

Indian Institute of Tropical Meteorology (IITM), Pune (1994) Severe rainstorms of India

Inter-Governmental Panel on Climate Change (IPCC) (2007) Fourth assessment Report

IPCC (1992) "Climate Change: The response Strategies". WMO/UNEP

IPCC (1998) Special report of IPCC working group iI. In: Watson RT et al (eds) Intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 517

Jain V, Sinha R (2003) River systems in the Gangetic plains and their comparison with the Siwaliks: a review. Curr Sci 84(8):1025–1033

Lal M (2001) Future climate change: implications for Indian summer monsoon and its variability. Curr Sci 81 (9):1205

Lyon-Caen H, Molnar P (1985) Gravity anomalies, flexure of the Indian plate and the structure, support and evolution of the Himalaya and Ganga Basin. Tectonics 4:513–538

Mall RK, Gupta A, Singh R, Singh RS, Rathore LS (2006) Water resources and climate change: an Indian perspective. Curr Sci 90(12):1610–1626

Milly PCD, Wetherald RT, Dunne KA, Delworth TL (2002) Increasing risk of great floods in a changing climate. Nature 415:514–517

Misra AK (2011) Impact of urbanization on the hydrology of Ganga Basin (India). Water Resour Manag 25:705–719. doi:10.1007/s11269-010-9722-9

Mitchell JFB, Karoly DJ, Hegerl GC, Zwiers FE, Marengo J (2001) Detection of climate change and attribution of causes. Climate change 2001: the scientific basis. Houghton JT et al. (ed) Cambridge University Press, 695–738

Molnar P (1984) Structure and tectonics of the Himalaya: constraints and implications of geophysical data. Ann Rev Earth Planet Sci V(12):489–518

Morrison J, Morikawa M, Murphy M, Schulte P (2009) Water scarcity & climate change: Growing risks for businesses & investors; a ceres report; Pacific Institute, 654 13th Street, Preservation Park, Oakland, CA 94612, www.pacinst.org

NIH (1993) Unpublished report, National Institute of Hydrology, Jal Vigyan Bhawan, Roorkee, India, SR–26

Pathak BD (1982) Ground water resources of Uttar Pradesh. In: Engineering Geosciences. Singhal BBS (ed), sarita parkashan, New Delhi, pp. 111–131

Post V (2003) Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during Holocene. Ph.D. Thesis, free Univ., The Netherlands

Quchi (1985) Response of alluvial rivers to slow active tectonic movement. Geol Soc Am Bull 96:504–515

Qureshy MN, Kumar S, Gupta GD (1989) The Himalayan megalineament–its geophysical characteristics. Mem Geol Soc India 12:207–222

Raikes RL (1968) Kalibangan: death from natural causes. Antiquity 63:286–291

Rao MBR (1973) The subsurface geology of the Indo-Gangetic Plains. J Geol Soc India 14:217–242

Ronen D, Magaritz M, Gvirtzman H, Garner W (1987) Microscale chemistry heterogeneity in groundwater. J Hydrol 92(1–2):173–178

Ruddiman WF (2001) Earth's climate. past and present. W. H. Freeman and Company, New York. Sahai, B. (1999) Unravelling the "Lost" Vedic Saraswati. Mem. Geol. Society India, 42:121–141

Rupa Kumar K, Krishna Kumar K, Pant GB (1994) Diurnal asymmetry of surface temperature trends over India. Geophys Res Lett 21:677–680

Saini HS (2008) Climate change and its future impact on the Indo-Gangetic Plain (IGP). e-J Earth Sci India I (III):138–147

Sarkar SK, Bhattacharya A, Bhattacharya B (2003) The river ganga of Northern India; an appraisal of its geomorphic and ecological changes. Water Sci Technol 48:121–128

Sastri VV, Bhandari LL, Raju ATR, Dutta AK (1971) Tectonic frame work and subsurface stratigraphy of the Ganga Basin. J Geol Soc India 12:222–233

Schmidhuber J, Tubiello F (2007) Global food security under climate change. PNAS 104(50):19703–19708

Schumm SA (1977) The fluvial system. Wiley, New York, 338

Seeber L, Armbruster J et al (1981) Great detachment earthquakes along the Himalyan arc and long term forecasts, Earthquake prediction. In: Simpson DW, Richards PG (eds) An international review. Maurice ewing series 4. Am Geophy Union, Washington, DC, pp 259–277

Sharma Y (1997) The Ganga; India (Book Chapter); Water pollution control. In Helmer R, Hespanhol I (ed), Publisher: E & FN Spon; London

Shina R (2005) Why do gangetic rivers aggrade or degrade. Curr Sci 89(5):836–840

Shina R, Jain V, Prasad babu G, Ghosh S (2005) Geomorphic characterization and diversity of the rivers of the gangetic Plains : Morphology, Processess and controls: Geomorphology 70(1–2).

Shiva V, Jalees K (2003) Sujalam: living waters. The impact of the river linking project. Jal Swaraj. Water Sovereignty series No. 2. NFSTE/Navdanya. New Delhi, 2003

Singh RL (1994) India: A regional geography, National Geographical Society of India. UBS Publishers Distribution Limited, Varanasi, pp 183–252

Singh IB (1996) Geological evolution of Ganga Plain-An Overview. J Palaeo Soc India 41:99–137

Singh N, Sontakke NA (2002) On climatic fluctuations and environmental changes of the Indo-gangetic Plains, India. Clim Chang 52:287–313

Singh IB, Ansari AA, Chandel RS, Misra A (1996) Neotectonic control on Drainage System in Gangetic Plain, Uttar Pradesh. J Geol Soc Ind 47:599–609

Sinha R, Friend PF (1994) River systems and their sediment flux, Indo-Gangetic plains, northern Bihar, India. Sedimentology 41:825–845.

Sinha Ray KC, Shewale MP (2001) Probability of occurrence of drought in various subdivisions of India. Mausam 52:541–546

Srinivasa Rao M, Srinivas K, Vanaja M, Rao GGSN, Venkateswarlu B, Ramakrishna YS (2009) Host plant (Ricinus communis Linn.) mediated effects of elevated CO_2 on growth performance of two insects folivores. Curr Sci 97(7):1047–1054

Statistical Yearbook for Asia and the Pacific (2007) Economic and Social Commission for Asia and the Pacific, United Nations, New York, 2007. See: http://www.unescap.org/STAT/data/syb2007/26-Wateruse-syb2007.asp

Trenberth KE (1999) Conceptual framework for changes of extremes of the hydrological cycle with climate change. Clim Chang 42:327–339

Wang YQ, Ruby Leung L, John L, McGregor, Lee D-K, Wang W-C, Ding Y, Kimura F (2004) Regional climate modelling: progress, challenges, and prospects. J Meteorol Soc Japan 82:1599–1628

Wild D, Francke C-J, Menzli P, Schön U (2007) Water: a market of the future–global trends open up new investment opportunities. Sustainability Asset Management (SAM) Study, Zurich

Wilhelmy H (1967) The shifting river; studies in the history of the Indus valley. Universitas 10:53–68