

Impact of climate change on the hydrological dynamics of River Ganga, India

C. K. Jain and Surya Singh

ABSTRACT

Rivers provide innumerable ecosystem services to mankind. However, anthropogenic activities have inflicted a host of pressures to the riverine ecosystems. Climate change is also one of the human induced consequences which is of serious concern. A number of studies have predicted devastating effects of climate change. In the Indian context, where a river such as the Ganga is already suffering from industrial and municipal waste disposal, unhygienic rituals, and other activities, effects of climate change may further aggravate the situation. Climate change will not only result in disasters, but effects on water quality, biodiversity, and other ecological processes also cannot be denied. In this paper, an attempt has been made to evaluate the effects of climatic change on the dynamics of River Ganga. The study focuses on the impacts on fundamental ecological processes, river water quality, effect on species composition, and hydropower potential etc. The paper also discusses management aspects and research needs for rejuvenation of the River Ganga.

Key words | biodiversity, climate change, hydrology, River Ganga, water quality

C. K. Jain
Surya Singh (corresponding author)
National Institute of Hydrology,
Roorkee 247 667,
India
E-mail: suryasingh.er@gmail.com

INTRODUCTION

Climatic variability and climate change have received significant attention from the scientific community across the globe. The basic reason underlying the fact that climate change is the most discussed topic in every forum is that climate affects all the spheres which all living organisms are exposed to. The ill-effects of adverse climate change can destabilize all the facets of the environment and thereby destabilize the bonds between the abiotic and biotic components of any ecosystem. The effects of global climate change are already visible in various components of the environment – glaciers are shrinking (Dyurgerov & Meier 2000) and ice is melting faster (Gregory *et al.* 2004; Overpeck *et al.* 2006; Stroeve *et al.* 2007), sea level is rising (Ramachandran *et al.* 2017), natural disasters such as floods, hurricanes, cyclones etc. are becoming more frequent and intense (Easterling *et al.* 2000; Aalst 2006; Coumou & Rahmstorf 2012; Majumder *et al.* 2017), floral and faunal ranges are shifting (Parmesan 2006; Wernberg

et al. 2011), and there are also effects on agriculture and the flowering pattern of plants (Fischer *et al.* 2005; Mall *et al.* 2006; Howden *et al.* 2007; Memmott *et al.* 2007). Almost all the ecosystems of the world are affected due to climate change. Rivers are also one of the most vulnerable ecosystems in the world. Moreover, rivers are considered as the most sensitive of all the ecosystems to the impacts of climate change, both directly and indirectly by the combination of various other stressors (Durance & Ormerod 2007, 2009). Impacts on the riverine ecosystem will not only affect the hydrology and dynamics of the river, but also pose serious threats to the survival and existence of a number of aquatic floral and faunal species, wild life, human population etc. Besides sustaining the life of organisms and providing plenty of ecosystem services, rivers are also a regulator of flood, sediment supplies, erosion, water quality and pollutant disposal etc. Mighty rivers such as the Ganga, Brahmaputra, Indus etc. also sustain many other ecosystems

such as wetlands, flood plains, estuaries and riparian areas etc. by providing water, nutrients, and energy. Thus, the effects of changing climate on the river will certainly influence many other associated ecosystems too. Therefore, study of the impacts of climate change on the rivers is of utmost importance.

The impact of climate change on a river brings a plethora of consequences which affect the entire dynamics of the river, such as water resource management (Middelkoop *et al.* 2001; Alcamo *et al.* 2007; Pahl-Wostl 2007; Kundzewicz *et al.* 2008), water quality (Delpla *et al.* 2009; Whitehead *et al.* 2009), eutrophication (Feuchtmayr *et al.* 2009; Rabalais *et al.* 2009; O'Neil *et al.* 2012), acidification (Sabine *et al.* 2004), accumulation of toxic substances (Gouin *et al.* 2013; Landis *et al.* 2013), hydromorphological changes (Boon & Raven 2012), catchment land-use changes (Oliver & Morecroft 2014), and invasion of exotic species (Hellmann *et al.* 2008; Rahel & Olden 2008) etc. A number of studies on the effects of climate change on riverine systems have also been carried out (Verghese & Iyer 1993; Gosain *et al.* 2006, 2011; Boon & Raven 2012; Hosterman *et al.* 2012; Deshpande *et al.* 2016; Hosseini *et al.* 2017). In India, rivers play a very important role and can be even considered as the lifeline of the nation. Rivers are the main source of irrigation in the agricultural sector, upon which more than 70% of the rural population depends. Apart from this, rivers are also a major source of potable water, transportation, hydropower, aquaculture, recreational activities etc. Among the 22 river basins across the country (CWC 2012), the Ganga river basin is the largest and most significant.

The River Ganga is one of the most important rivers in India. Being the largest river, Ganga supports the livelihoods of millions of people and there are many important cities and industries along its bank. However, over the years the river has faced severe negligence. Unsustainable dam construction and water diversion into the canals resulted in very low flow in the main river in several stretches. The situation further worsened due to the discharge of millions of liters of untreated industrial effluents and municipal sewage per day from nearby towns/cities. Considering the urgency of the situation and to target the escalating pollution problems, the Government of India launched an ambitious plan named the Ganga Action Plan (GAP) in

1986. However, the plan failed due to the consideration of limited issues, under-utilization of sewage treatment plants (STPs), lack of technical expertise and political will, and many other implementation issues. In 2007, the River Ganga was declared the fifth most polluted river in the world (Rai 2013). To intensify the Ganga rejuvenation efforts and create more awareness regarding pollution prevention, the River Ganga was affirmed the status of 'National River of India' in November 2008. Later on, many other programmes were launched (e.g. Namami Gange, National Mission for Clean Ganga etc.) and various authorities were established (e.g. National Ganga River Basin Authority etc.) to revive the river, but to date the situation has not improved (Das & Tamminga 2012). In such circumstances, impacts of climate change may prove to be a major setback for the river. Further, these effects may be more stringent and influential for the River Ganga considering the large area under impact. Interaction of the increasing temperature and changing discharge patterns owing to climate change, along with other existing pressures on River Ganga, will affect the survival of millions of people and various floral and faunal species. Negative impacts on other hydrological and ecological processes also cannot be neglected. Therefore, in this paper efforts have been made to assess the impacts of climate change on the various aspects of the riverine dynamics of River Ganga.

RIVER GANGA: ORIGIN, EXPANSE AND CULTURAL SIGNIFICANCE

River Ganga originates from Gaumukh in the Gangotri glacier at 30°55' N and 79°7' E at about 4,100 m above mean sea level in the Uttarkashi district of Uttarakhand, India. The Gangetic ecosystem is one of the most vivid and complex ecosystems, on which approximately 445 million people are dependent either directly or indirectly (Lokgariwar *et al.* 2014). The Ganga river basin is the largest among all the river basins in India, and the fourth largest in the world. The basin is part of the Ganga-Brahmaputra-Meghna basin, which drains through China (4%), Nepal (13%), India (79%) and Bangladesh (4%) (Nepal & Shrestha 2015). In India, the Ganga basin lies in the states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, West

Bengal, Rajasthan, Madhya Pradesh, Haryana, Himachal Pradesh and Delhi. In northern India, the catchment of the Ganga basin is one of the largest water catchments, draining an area of approximately 1.09 million km² (Bharati *et al.* 2011). The 2,525 km river, flowing through the states of Uttarakhand and Uttar Pradesh (1,425 km), Bihar and Jharkhand (475 km) and West Bengal (625 km), touches 44% of the Indian population before flowing through

Bangladesh and emptying into the Bay of Bengal (Figure 1). Originating in the mighty Himalayas, the Ganga has a very fertile and large basin that accounts for 30% of India's cultivable land. In addition to its economic and ecological relevance, it also has a strong cultural presence among Indians. Nevertheless, the River Ganga is an integral part of Indian spirituality. There are many mythological statements on this river and hence, millions of Ganga devotees

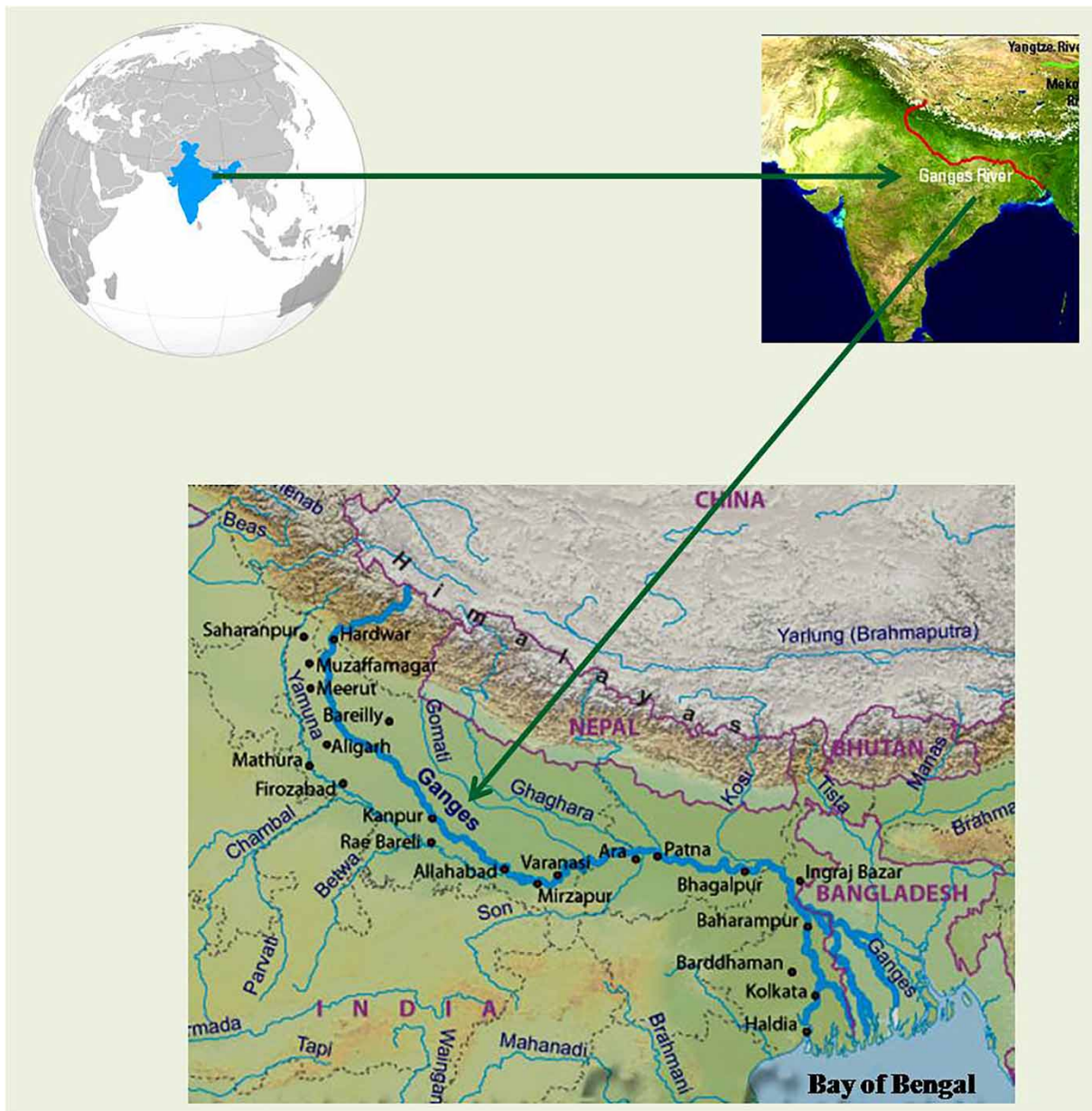


Figure 1 | Location of River Ganga.

through to the river just to have a holy dip (Lokgariwar *et al.* 2014; Sanghi 2014). However, there is a lack of effort to understand how this massive river is responding to climate change along its basin. Climate change will have a considerable impact on the dynamics of the river Ganga. This will directly affect a major portion of northern India, which depends on the river for meeting domestic, agricultural, and industrial water needs.

FACTORS RESPONSIBLE FOR CHANGES IN THE DYNAMICS OF RIVER GANGA

Temperature and precipitation patterns

An increasing trend in the temperature of the Indian subcontinent is evident from the pattern shown in Figure 2. In the coming years, the rise in temperature will be much more severe and rapid (Diffenbaugh & Field 2013). According to an estimate, the average global temperature is likely to increase by 1.8–4.0 °C (IPCC 2007). Rising atmospheric temperature is expected to increase the water temperature as well. Since rivers are turbulent and are in close contact with atmospheric air, they respond to atmospheric warming very quickly. It is supposed that there will be an increase in the surface water temperature of streams. Regional climate model studies in the Ganges basin predict

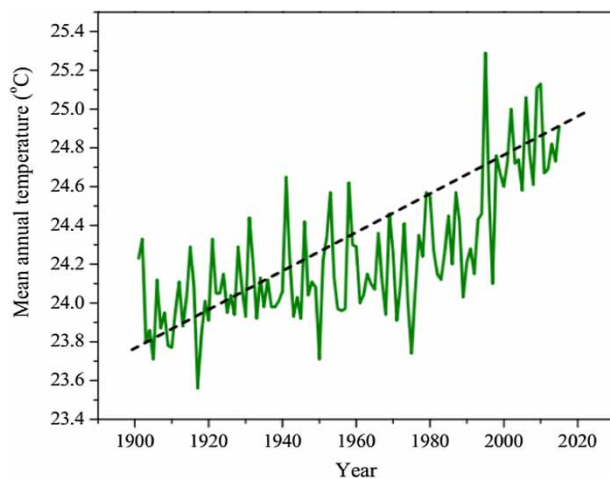


Figure 2 | Trend of average annual temperature in the Indian subcontinent during 1900–2015 (Data source: <https://data.gov.in/>).

an increase in the mean annual temperature of 1–4 °C between 2010 and 2050 (Moors *et al.* 2011). A study on the Koshi river basin, a sub-basin of the Ganges, also reveals increasing trends in the seasonal maximum and minimum temperatures (Shrestha *et al.* 2017). Due to the warming of climate, there may also be a change in winter precipitation from snow to rain. This eventually may lead to a change in the flow of the river (Kundzewicz *et al.* 2008).

There are other factors which also influence the river temperature and heat budget. The heating of river water depends on the amount of solar insolation received and radiated back; resistance for the heat flow offered by the river banks to the river bed; heat flow transfer between river and surrounding air, river bank, and land; evaporation and condensation mechanisms etc. Moreover, rivers also receive heat from the water coming from their catchment areas (Webb *et al.* 2008). A combination of all these factors will influence the hydrological cycle. In response to warming climate, the hydrological cycle is expected to intensify. Since the warm air can hold more water vapor, the resulting precipitation will be much more intense. Nevertheless, due to warming climate, rainfall will replace snowfall. As drier atmospheric conditions will result in increased drying of the land surface, it will put additional pressure on the river to fulfill the water demand.

Affected by the temperature variation, precipitation is also expected to show changes (Shrestha *et al.* 2017). Studies prove that there will be a mixed pattern of changes in precipitation – in some seasons higher rainfall may result in floods while in others extreme drought conditions may prevail due to high temperatures. Changing precipitation patterns during summer and winter are also expected to increase the nutrient loading in rivers from increased erosion of agricultural soils and associated catchment areas (Rahman *et al.* 2016). As the pattern and intensity of precipitation will change, flow in the rivers is also expected to change. This may have a significant effect on the habitats and communities of the river ecosystem. Another impact of diminished flows is on the concentration of dissolved oxygen (DO) levels. Reduced flow conditions result in a marked decrease in DO concentration, which ultimately enhances the chances of eutrophic conditions in rivers

(Bocaniov *et al.* 2016). Higher evaporation rates coupled with reduced precipitation will lead to the continued lowering of water tables, which will eventually also lead to a reduction in groundwater levels.

High concentration of atmospheric CO₂

Exceedingly high concentrations of CO₂ may enhance the carbonic acid concentration in the river waters. The upper safe limit for CO₂ concentration in the atmosphere is considered to be 350 ppm. However, higher emission from various anthropogenic sources had increased atmospheric CO₂ concentrations to 406.82 ppm by 2017 (Figure 3). Research suggests that excess CO₂ present in the atmosphere is dissolved in rainwater, resulting in the formation of carbonic acid (H₂CO₃). Upon contact with rock surfaces, such waters enhance the dissolution of rock surfaces, thereby speeding up the chemical weathering processes (Beaulieu *et al.* 2012). In the long term, this may result in much higher sediment loads on the river.

River Ganga is thought to carry approximately 403–660 × 10⁶ tonnes of sediments annually (Subramanian & Ramanathan 1996), of which 88% of the annual sediment load is restricted to only during monsoons (Subramanian 1996). Therefore, further enhancement in the sediment loads will have an impact on the overall ecological characteristics as well as the water quality of the river.

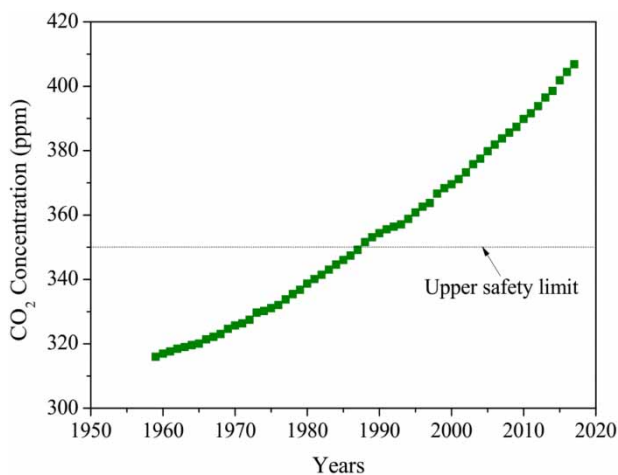


Figure 3 | Carbon dioxide concentration in the atmosphere (1960–2017) (Data source: Mauna Loa Observatory, Hawaii).

Glacial retreat, runoff and river responses

The fast melting of mountain glaciers results in changes in the discharge regimes of rivers originating from glaciers (Milner *et al.* 2009; Bliss *et al.* 2014). Glaciers influence the flow of water in rivers, as they are the natural keepers and controllers of fresh water flow to the rivers. As the increasing temperature is resulting in fast melting of glaciers, it may result in floods and other disasters in the rivers (Lutz *et al.* 2014). Gangotri glacier in the Uttarkashi district of Garhwal Himalaya, which is the feeding glacier of River Ganga, is retreating at a fast rate owing to increasing temperature and climate change. It has been reported that the average rate of glacier retreat is 19 m/year (Naithani *et al.* 2001). Remote sensing images reveal that this glacier has been receding since 1780; however, the retreat has increased since 1971 (Figure 4). In the last 25 years of the 20th century, it has shrunk more than 850 m (Sharma & Owen 1996). This will have a serious impact on the flow characteristics of the Ganga (Bolch *et al.* 2012; Immerzeel *et al.* 2012; Kääb *et al.* 2012). It has been reported that between 2003 and 2009, approximately 174 gigatonnes of water was lost by Himalayan glaciers, which led to severe floods in the Indus, Ganga, and Brahmaputra rivers affecting millions of lives (Gardner *et al.* 2013; Laghari 2013).

In warmer climates it is also expected that a large amount of precipitation will occur in the form of rain, rather than snow (Trenberth 2011). This can have serious implications on the river water and basin area. Precipitation in the form of snow results in slow melting of ice and therefore, allows a continuous water supply to the river stream. However, rains will immediately fill up the water bodies, resulting in floods in the basin area. It has many other related consequences. Frequent rains will also result in increased soil erosion, thereby silting the rivers, which will further aggravate the flood situation (Ghosh & Mistri 2015). Faster run-off from catchment areas to the river may also result in a decline in the groundwater table and soil moisture, as the over-flowing water will not have sufficient time to recharge the groundwater. In the long term, this could have very serious implications for the overall groundwater availability, soil productivity, agricultural output, and therefore on the entire population depending upon the river (Kumar 2012; Kidmose *et al.* 2013; Taylor *et al.* 2013).



Figure 4 | Retreat of Gangotri glacier (1780–2001) (Image source: <https://earthobservatory.nasa.gov>).

IMPACTS OF CLIMATE CHANGE ON RIVER GANGA

The changing temperature and precipitation patterns, fast glacial retreat, and increasing CO₂ concentration will have a number of subsidiary effects on the river, as discussed below.

Changes in the fundamental ecological processes

Fundamental ecological processes in any freshwater aquatic ecosystem include production and decomposition patterns, nutrient cycling, and energy flow etc. Temperature change affects the productivity of the aquatic ecosystem to a significant extent. Primary productivity may increase in response to an increase in the length of the growing season and increase in nutrient release from catchment soils. This will alter the food-web structure in river water, leading to higher phytoplankton biomass and thereby a decrease in benthic oxygen concentrations as well as an increase in nutrient release from sediments (Jeppesen *et al.* 2009). Higher suspended sediment loads will also increase the turbidity of the river body (Miller *et al.* 2015), therefore changing the underwater light regime. It will have adverse impacts on the growth of submerged aquatic plants.

However, after some time this increasing productivity trend will begin to decline, because the rate of respiration also increases along with the increasing temperature, which again becomes a reason for increasing CO₂. Decomposition processes also become enhanced due to higher temperatures. Once these productivity and decomposition patterns are altered, this also affects the nutrient cycling as well as the energy flow. Thus, the increasing temperature will have a significant impact on the fundamental processes of the river ecosystem.

Changes in the hydrologic characteristics of aquatic systems

Erratic rainfall patterns are not only the cause of severe floods and droughts, but are also responsible for disturbances in the discharge pattern of the river. The flow conditions of the river determine many of the characteristics, of which water quality is one. During very high discharge periods, water quality shows variations due to the mixing of waters of different origins, such as surface run-off, underground water, and water which circulates within the soil. All these waters have many different characteristics; for instance, water coming through surface run-off

usually carries suspended solids along with other impurities. Water which circulates within the soil is the source of dissolved organic carbon, nitrogen, and phosphorus. Moreover, groundwater is mostly the source of silicate, calcium, magnesium, sodium, and potassium. Therefore, discharge changes lead to a change in the ambient water quality to a great extent.

River water quality

There will be colossal changes in river water quality owing to increasing temperature and global warming (Hassan *et al.* 1998; Jun *et al.* 2010; Rehana & Mujumdar 2011; Todd *et al.* 2012). Increased temperature of the river water will influence the growth rate of phytoplankton, macrophytes, aquatic organisms, and other species, as many of the chemical and biological processes run at a faster pace at high temperatures. As per the Arrhenius relation, the kinetics of a given chemical reaction can be doubled for a temperature increase of 10 °C. Thus, it is expected that dissolution, solubilization, complexation, degradation and many other such

effects may take place at a faster pace owing to increased temperature due to global warming. Increased temperature will also influence the growth rate of phytoplankton and bacteria (Whitehead & Hornberger 1984; Wade *et al.* 2002; Sakyi & Asare 2012), which in turn will stimulate the process of eutrophication, thus causing the river water quality to deteriorate. Faster kinetics will also lead to faster dissociation of water molecules, thus making water more acidic. In the dry season, due to the high rate of evaporation and faster reactions, biochemical oxygen demand (BOD) will be high (Figure 5). Further, irregular and intense rainfall may also result in higher run-off from the catchment area, thus resulting in higher loads of suspended solids and sediments, contaminants, and increased soil erosion (Leemans & Kleidon 2002; Lane *et al.* 2007).

There are several water quality parameters on which climate change will have a significant impact, such as temperature, pH, DO, dissolved organic matter, micropollutants, various microorganisms etc. As stated above, an increase in temperature will lead to faster kinetics of several biochemical reactions, which will result in a concentration

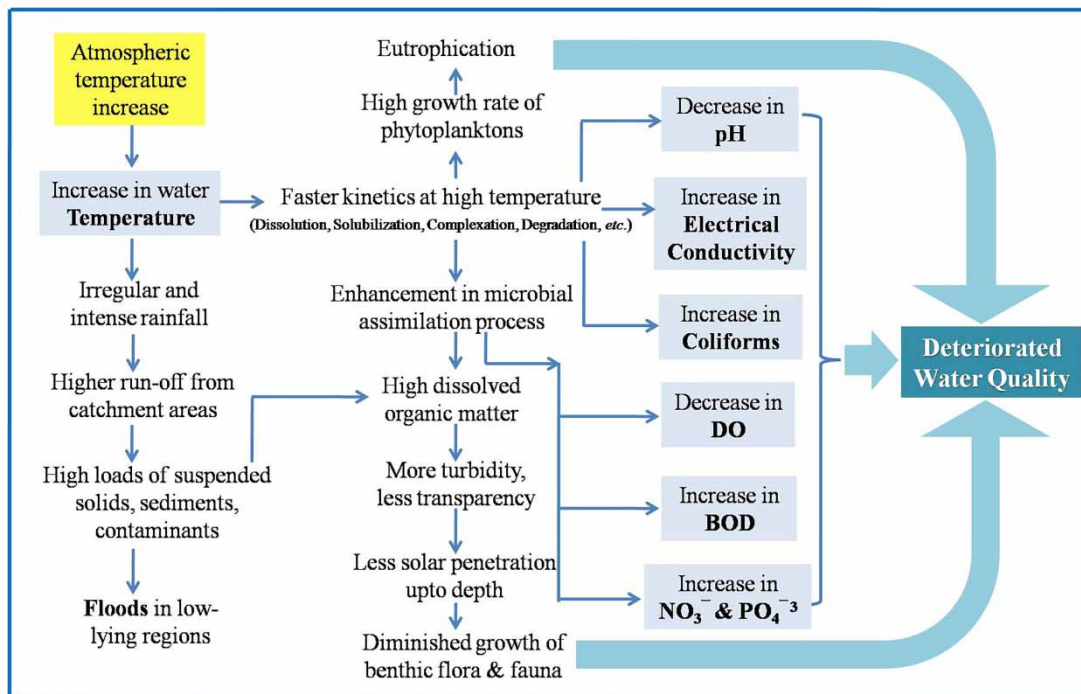


Figure 5 | Impact of climatic change on water quality.

increase of dissolved substances and decrease in DO content. The saturation concentration of DO decreases almost 10% with a 3 °C increase (Delpla *et al.* 2009). A decrease in DO can be linked to an enhancement in the microbial assimilation process of biodegradable organic matter, which ultimately results in dissolved organic carbon (Prathumratana *et al.* 2008).

Dissolved organic matter is also an important factor to be considered as it affects the ecosystem functioning by influencing sunlight absorbance, energy and nutrient supply, acidity etc. Higher dissolved organic matter will result in low transparency and thus less solar penetration up to the depth of the river. It will have implications for the growth of benthic flora and fauna. In warmer climates, blue-green algae (cyanobacteria) may also flourish. It has been reported that global warming increases the total abundance and proportions of warm water species such as green algae and diatoms in the water (Daufresne & Boët 2007). An increase in water temperature may also increase the pesticide concentration, as surface waters are the immediate receptors of pesticide contamination from agricultural fields. Warming climate and changes in rainfall patterns as well as intensity may also influence pesticides' ultimate fate (Bloomfield *et al.* 2006).

Effect on species composition

As the atmospheric temperature rises, the water temperature increases as well, which ultimately affects the species diversity. Climate change is expected to affect all the levels of riverine biodiversity, from species to biome levels (Learmonth *et al.* 2006; Bellard *et al.* 2012). As many of the species in the Gangetic ecosystem are already threatened, climate change effects will further complicate the situation. Habitat loss is expected for the species which have comparatively narrower distribution and in the locations where the temperature increase will be higher (Eaton & Scheller 1996). Temperature change will also affect species composition and abundance, as well as the occurrence of scarce and/or non-native species (Daufresne *et al.* 2009). According to Bergmann's rule of thermal regulation, species tend to be smaller in warmer climates. Therefore, a reduction in the body size of the species is also expected owing to increased water temperature.

Endemic taxa will be threatened both by habitat loss and as a result of reduced connectivity between habitats, especially if water-flow connections are lost. There is also the risk of deoxygenation due to increased temperatures. This problem can be further aggravated if there is enhancement in plant growth due to high water temperature and unlimited nutrient supply, which can lead to further low levels of oxygen and risk for the aquatic faunal species (Whitehead *et al.* 2009). These environmental changes will further result in significant modifications in the distribution of species, higher susceptibility to alien species invasion, and overall biodiversity reduction that may eventually lead to impaired ecosystem services.

Climate change also has very negative effects on the specific biota of the River Ganga. Ganga is home to a number of fish species, reptiles, birds, and mammals. Endangered species such as the Gangetic Dolphin (*Platanista gangetica gangetica*), Ganges softshell turtle (*Nilssonia gangetica*), Gharial (*Gavialis gangeticus*), Himalayan Mahseer (*Tor putitora*) etc. are already under severe threat. These species are heading towards a higher extinction risk every passing year (Figure 6). The Gangetic Dolphin, which was 'vulnerable' up to 1990, was moved into the 'endangered' category in 2004. Likewise, Gharial moved to the 'critically endangered' category from 'endangered' in 2007. Changing climate will further diminish their chances of survival. Increased temperature affects the prey population for dolphins. Changing climatic patterns may also alter the water current and flow characteristics of the river, which will further intensify the problem due to

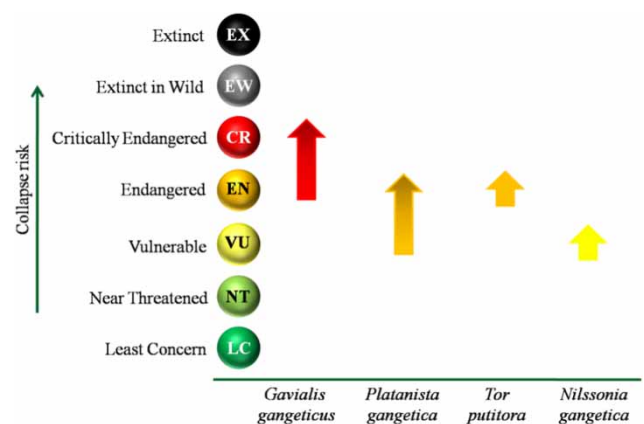


Figure 6 | Extinction risk of fauna in the Gangetic ecosystem.

changed prey distribution, feeding grounds, changes in trophic relationships, community structure, migratory pathways, and lower reproductive success, ultimately leading to lower chances of survival (Smith *et al.* 2009; Simmonds & Elliott 2009; Smith & Reeves 2012). For example, dolphins depend upon echolocation for finding their food; hence, changes in river flow and depth will adversely affect their distribution and survival. Warmer water may also affect the health of the river dolphins due to thermoregulatory issues and increase in exposure to toxic algal blooms.

Phenology and predator–prey interactions in riverine ecosystems

Increasing global temperature will also affect the phenology of the vegetation community as well as animals in the freshwater ecosystem (Walther *et al.* 2002; Visser & Both 2005; Cleland *et al.* 2007; Anderson *et al.* 2013). While the floral community may flourish more due to rising temperatures, the consumption pattern of faunal species will also change accordingly. Temperature increase may alter the growing season, pollination, and flowering pattern of many species (Khanduri *et al.* 2008). It will have a direct or indirect impact on the overall plant fitness (Galen & Stanton 1991, 1993). The warming temperature of water may also produce a change in the interaction patterns of algae and herbivores. Range shift is another consequence of a disturbed ecosystem. Due to changes in the surrounding water temperature, species tend to shift their ranges to a more habitable region. All the aquatic faunal species which are dependent on the phytoplankton predator–prey may not move at a similar pace to that of the phytoplankton. This mismatch may lead to a decline in some of the species (Winder & Schindler 2004; Walther 2010). Further, overconsumption of autotrophs by herbivores can disturb the entire ecosystem, as climate change can also result in changes in the feeding pattern of many species owing to the changes in food availability and requirements (Stenseth *et al.* 2002). Increased water temperature will also lead to changes in the food-web structure, with higher winter survival of fish and a general switch from dominance of zooplankton and aquatic macrophytes to fish and phytoplankton. In rivers, increased temperature will cause stress for fish and invertebrates with high oxygen requirements,

leading to changes in community composition. The population of some of the aquatic faunal species may also face the danger of extinction if the physiological processes are not able to be in sync with the phenological changes.

A change in predator–prey interactions is another significant repercussion of climate change (Abrahams *et al.* 2007; Broitman *et al.* 2009). In the Gangetic ecosystem, the fish community, fish-eaters, and their prey are ectothermic. Therefore, a change in the surrounding water temperature will influence the energy needs or food requirements of these species. Higher temperature results in faster metabolism, leading to a higher energy requirement; this refers to increased interactions between predator and prey. The influencing parameters of the water affecting predator–prey interactions will be temperature, DO, and turbidity (Abrahams *et al.* 2007). It has been shown in Figure 5 that under elevated water temperature conditions, DO will be decreased while turbidity will be enhanced. In the reduced DO concentration conditions, many of the prey species would try to avoid being predated by deliberately moving towards hypoxic environments. Thus, a hypoxic environment will act as a shelter for the prey species and a barrier for the predator (Figure 7). Turbidity will have its impact on the process of prey detection by predators and subsequent survival efforts of the prey species. Due to the turbid water conditions, prey will become unable to mark the presence of its predator well ahead of time (Figure 7), and hence the chances of its survival will reduce (Miner & Stein 1996).

Hydropower potential of the river

As hydroenergy is solely dependent on water resources, climate change impacts on rivers will certainly affect the hydroenergy potential of India (Pathak 2010). India is the seventh largest producer of hydroelectric power in the world. By 2017, India's installed hydroelectric power capacity was about 13.5% of the total power generation capacity (GoI Report 2017). The River Ganga is known to support a number of hydropower projects in approximately 10 states of the country, the highest being in the state of Uttarakhand. Moreover, the Ganga basin will have the highest dam density in the Himalayan region if all the ongoing and proposed dams are constructed (Pandit &

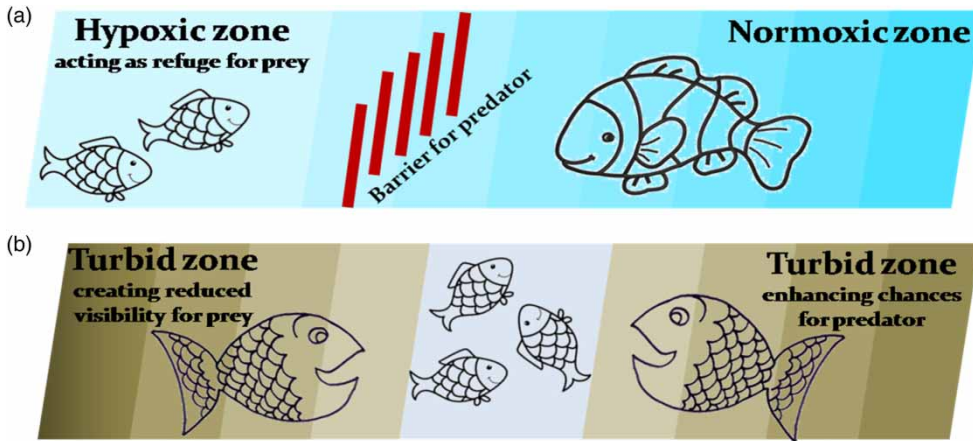


Figure 7 | Predator–prey interaction: (a) effect of DO, (b) effect of turbidity.

Grumbine 2012). Therefore, it is necessary to understand the impacts of climate change on the hydropower potential of River Ganga. In hydropower production, the amount of electricity generated in a dam/reservoir is dependent on the quantity of the water passing through the turbine, the water head, and the mechanical efficiency of the turbine. Water passing through the turbine further depends on the seasonal and quantitative changes in precipitation pattern and evapotranspiration (Koch *et al.* 2011). Therefore, changes in climate resulting in variability in temperature, precipitation and run-off will certainly have an impact on the hydropower potential of the dams and reservoirs. Besides reservoirs, the run-off-river hydropower potential will also be disturbed to a great extent. A number of case studies have been carried out in the past depicting the negative impacts of climate change on overall hydropower production (Madani & Lund 2010; Chiang *et al.* 2013; Kachaje *et al.* 2016; Tarroja *et al.* 2016). Basically, climate change will influence hydropower production through two variables: discharge and head. Variation in the discharge pattern of the river may disturb the continuous water availability to power stations. Whereas less discharge is expected to reduce the power production, high discharge for a few months followed by a longer dry period may result in increased spill, thereby again rendering decreased power generation. Reduced precipitation events will also reduce the required head level in the reservoirs, as low inflow will result in lower water levels. Moreover, variation in temperature and precipitation intricately influences a

number of factors, which ultimately result in reduced hydropower production, as depicted in Figure 8. Negative impacts on the hydropower generation owing to variable climate will certainly have an effect on the entire scenario of the energy sector. In such situations, dependency on existing conventional fossil fuels may increase, which will further contribute to climate change.

MANAGEMENT ASPECTS AND RESEARCH PRIORITIES

The above discussion reveals that undoubtedly, climate change impacts will prove to be disastrous not only for the river but also for the millions of people who are directly or indirectly dependent on it. In order to attenuate the impacts, significant efforts are required to be undertaken. A proactive approach is essential to find suitable ways of dealing with the situation. Research into the dynamic aspects of a riverine ecosystem, stormwater management, river catchment management, aquatic ecology and related features is essential. Further, accepting the fact that climate change is already taking place, adaptive approaches also need to evolve. Although rivers, being dynamic entities, are continuously adapting themselves, current climate changes are occurring at a much faster rate than the adaptive capability of the rivers. Moreover, a reactive approach is the ultimate solution to overcome the impacts due to climate change-induced disasters. Thus, a combination of these approaches

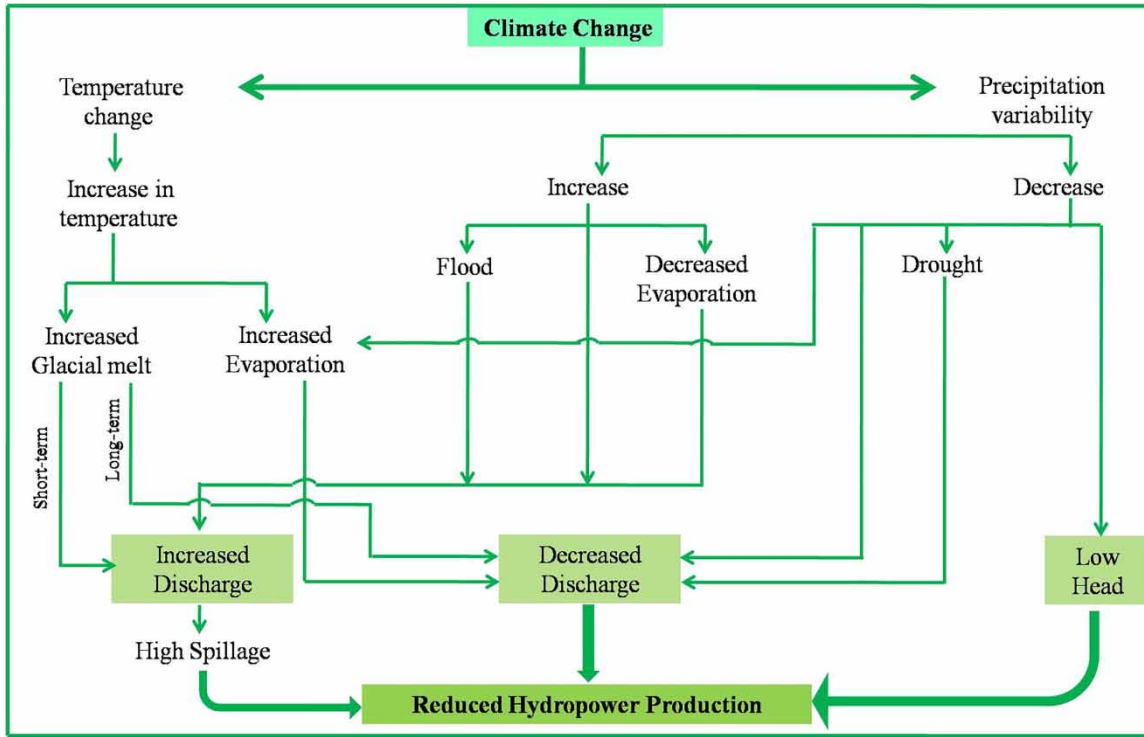


Figure 8 | Impact of climate change on hydropower production.

will hopefully bring resilience to the dynamics of River Ganga (Figure 9).

Changes in the basic hydrological aspects of the river would influence many of the related ecological processes such as energy flow pattern, biogeochemical cycles, productivity in the riverine ecosystem, decomposition processes, predator-prey interactions, inter-specific

competition etc. (Traill *et al.* 2010). In order to sustain ecological processes, it is imperative to identify the key species that are responsible for the ecosystem’s resilience. It has been found that high species richness is able to sustain the ecosystem very well under stressed conditions (Loreau *et al.* 2001); therefore, those species which are known to have lesser functions may prove to be highly beneficial in the longer term. Considering these facts, more research needs to focus on the assessment of species diversity in the Gangetic ecosystem. In order to assess the threats to the Gangetic ecosystem, continuous research is also necessary for finding the response of aquatic floral and faunal species towards various extrinsic factors. More emphasis should be given to finding the processes and mechanisms through which changes are taking place in the behaviour, physiology, and evolution of species along with mechanisms affecting intra- and inter-specific relations. In order to avoid range shifting of various micro- and macrospecies of the Gangetic ecosystem, research is required to understand the life history and ecology of the species (Palmer *et al.* 2009). It is imperative to

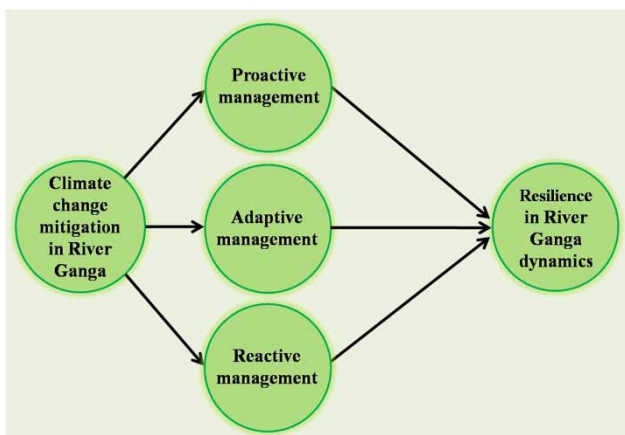


Figure 9 | Management strategy for the River Ganga.

say that in dynamic riverine ecosystems, the effects of change may sometimes also be reversed by various ecosystem processes (Suttle *et al.* 2007).

In order to attenuate the adverse impacts of climate change, a number of adaptive management strategies also need to be adopted in the Ganga basin. Existing causes of stress in the river, such as point and non-point pollution, water abstraction, increasing number of dams/reservoirs etc., need to be curtailed. There is a need to enhance and strengthen the conservation measures also, not only for the river but also for the adjacent catchment area. Plantations along the riparian area may help to slow down the silting and flood situation. The establishment of drought tolerant plant species may also help to prevent erosion of the river bank in high temperature conditions. Moreover, appropriate environmental flow needs to be maintained in the Ganga, especially in the middle and lower reaches, so that the river may recuperate. Invasive plant species which can threaten the native species should be removed. There is also a need to know the features at gene, population, community, and ecosystem levels which may provide better chances of survival to the organisms. Apart from adopting various protective measures for the river, significant efforts are also required to control allied activities such as forestry and related land uses, grazing, farming, dam/reservoir management etc. (Arthington *et al.* 2006).

As already stated, severe rainfall resulting from extreme weather events may lead to floods and subsequently significant erosion of river banks and catchment areas. Therefore, river restoration projects need to be executed well ahead of time to avoid grave consequences. In order to reduce high energy flow and for improvement in river water quality, additional water bodies may be created as storage basins, which will be adjacent to the Ganga river and have linkages with the main channel. Wetland creation and the development of storm water infrastructure may also result in a positive outcome (Poff 2002). For better preparedness and quick response action, strengthening of water monitoring networks and weather forecasting systems is essential. River flow monitoring on a regular basis is also essential to determine the climate change-induced alterations in flow pattern (Palmer *et al.* 2009). There should also be efforts for the management of nearby land areas, and anthropogenic activities should be minimized. Infrastructure development and industrial agglomeration along the river need to be curtailed in order to lessen the pollution load in the river.

Another very significant aspect in the management of the river is effective policy planning. Past experiences show that due to lack of coordination among various monitoring agencies involved, the expected results could not be achieved. As the River Ganga flows through five states, coordinated efforts are required to execute any plan. Besides the involvement of a central agency, state boards and municipal

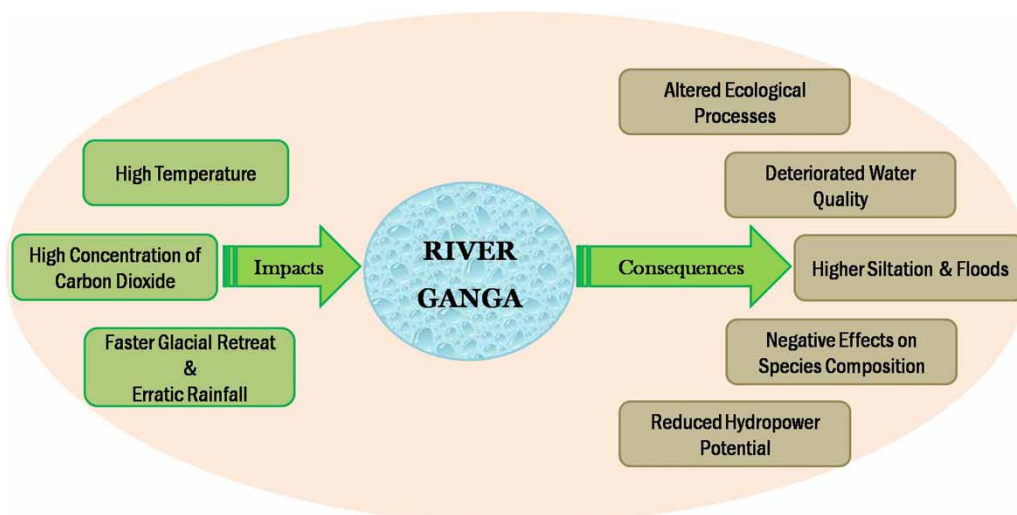


Figure 10 | Impact of climate change on the dynamics of River Ganga.

authorities should also be involved. Public participation is also essential in governing water-related issues. Thus, a decentralized approach to planning is vital for the effective implementation of schemes and positive outcomes.

CONCLUSIONS

Conservation and management of the River Ganga is a national priority (Figure 10). Since time immemorial it has been the most revered river in the country. Besides providing a host of ecosystem services, the River Ganga has also played a very important role in the growth and development of the economy by contributing to the agricultural sector, industrial sector, hydropower generation, tourism, and other recreational activities. However, due to increased urbanization and industrialization, there has been a colossal loss in the pristine quality of the river. The effects of climate change will further add to the pitiable condition of the river and in coming years, these risks will be much more intense. Climate change impacts will not only result in severe disasters of floods and drought, but will also reduce the carrying capacity as well as assimilative capacity of the river by affecting its abiotic and biotic components. Therefore, immediate efforts are required in order to reduce any further degradation of the river ecosystem. Despite a number of action plans executed in the past few decades, there is still much to be done. More concerted efforts are required in the direction of climate change management. Plans related to the control of pollution in the River Ganga need to be intermingled with climate change management efforts by employing better policy planning. There is also a need to learn from the experiences gained in the past. Moreover, bridging the gap between scientific/technical interventions and spiritual consciousness can be an effective step for the rejuvenation of the River Ganga.

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