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Environmental, geological and economic effects of climate change on the Indian hydrology: A review

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ABSTRACT

Over the last few years, global temperature has increased rapidly and continuously at around 0.2 °C per decade. Climate change is expected to have considerable impacts on natural resource systems, which, in turn, can lead to instability and conflict, displacement of people and changes in occupancy and migration patterns. Rise in atmospheric temperature due to climate change will lead to loss of glaciers in the Himalayas, which, in turn, may reduce water availability in the rivers of Indus – Ganga plains, especially in dry seasons. The response of hydrological systems, erosion processes and sedimentation in the Himalayan region could alter significantly due to climate change. During the twentieth century, majority of the Himalayan glaciers have shown recession in their frontal parts, besides thinning of the ice mass. Retreat in glaciers can destabilize surrounding slopes and may give rise to catastrophic landslides and floods. The melting of ice is changing the hydrological cycles and is also affecting the ocean currents. Many of India's coastal aquifers are already experiencing salinity ingress including Saurashtra coast in Gujarat and Minjur aquifer in Tamil Nadu. Increasing frequency and intensity of droughts in the catchment area will lead to more serious and frequent salt-water intrusion in the estuary and thus can deteriorate surface and groundwater quality and agricultural productivity. A warmer climate will change the patterns of hydrological cycle, which, in turn, can alter the intensity and timing of rainfall. Mahi, Pennar, Sabarmati and Tapi rivers will face water shortage conditions in response to climate change. River basins belonging to Godavari, Brahmani and Mahanadi may not face water shortages, but severity of flood shall increase in these areas. In future, there will be a net reduction of groundwater recharge and greater summer soil moisture deficits because higher temperature can shorten the duration of recharge seasons. Production of rice, maize and wheat in the past few decades has declined in many parts of Asia due to water shortage. Linking the concept of sustainable development to climate change can provide a deep insight into the proper methods of long term societal responses to global environmental change.

***Keywords*:** water; climate change; river basin; glacier; groundwater

1. INTRODUCTION

Water is a basic resource which is intimately linked with food security, human health and environmental protection. Rapid population growth, increasing urbanization, industrialization and pollution threaten the sustainability of our water resources. Natural climate variability and human-induced climate change add to those threats, particularly in developing countries where the impacts are potentially great and the capacity to cope is comparatively weaker.

Since industrialization, human activities have significantly altered the atmospheric composition, leading to climate change of an unprecedented character. Climate is the long-term statistical expression of short-term weather. Climate may change in different ways, over different time scales and at different geographical scales. The overall state of the global climate is determined by the amount of energy stored by the climate system, and in particular the balance between energy the earth receives from the sun and the energy which the earth releases back to space, which in total is called the global energy balance (Maslin, 2004). How this energy balance is regulated depends upon the flows of energy within the global climate system. Major causes of climate change involve any process that can alter the global energy balance, and the energy flows within the climate system.

Throughout the earth's history climate has fluctuated between warm and relative cold phases. In the last 100 years, the earth's surface and lowest part of the atmosphere have warmed up on average by about 0.6 °C (IPCC, 2007). During this period, the amount of greenhouse gases in the atmosphere has increased, largely as a result of the burning of fossil fuels for energy and transportation, and land use changes for food by mankind. Increase in the atmospheric concentrations of important anthropogenic greenhouse gases like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3) are considered to be the driving forces for such climatic changes (IPCC, 2007). This measure is an average over both space (globally across the land-surface air, up to about 1.5 m above the ground, and sea-surface temperature to around 1 m depth) and time (an annual mean over a defined time period).

In the past few decades scientists have assembled considerable amount of database which speak in favour of the causes and projected impacts of the growing concern of climate change. United Nations Framework Convention on Climate Change defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". Without urgent and concerted actions, it will damage fragile ecosystems, impede development efforts, increase risks to public health, frustrate poverty alleviation programs, and force large-scale migration from water or food-scarce regions (IPCC, 2007). On the other hand, global warming is the increase in the average measured temperature of the earth's near-surface air and oceans since the mid-20th century, and its projected continuation.

‘Global warming’ is quite different from ‘climate change’, which is a more complex phenomenon. Climate change can occur in different ways such as changes in regional and global temperature, changes in rainfall patterns, expansion and contraction of ice-sheets, sea level variation, plate tectonics, volcanism, ocean variability etc; temperature is not the only changing factor in case of climate change (Maslin, 2004).

An analysis of the seasonal and annual air temperatures from 1881 to 1997 indicated that there has been an increasing trend of mean annual temperature by the rate of 0.57 °C per 100 years (Pant and Kumar, 1997). The trend and magnitude of global warming over India over last century has been observed to be broadly consistent with the global trend and magnitude (Ministry of water resources, 2008).

In India, warming is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any part of country except for significant negative trend over Northwest India. Examination of long-term variation in the annual mean temperature of industrial and densely populated cities like Bombay and Calcutta has shown increasing trend in annual mean temperature (at Bombay and Calcutta by 0.84 °C and 1.39 °C per 100 years, respectively) (Hingane, 1985). These warming rates are much higher than the values reported for the country as a whole.

Water is a compound whose material constitution becomes secondary to its symbolic value because of its reflection in our mind as a symbol of life. Despite significant progress of human society, water related problems are continuously affecting the social infrastructures and jeopardizing the productivity of the society, which in turn, are depriving the common people of adequate amount of clean water. Climate change is expected to have considerable impacts on water resources in India, which, in turn, can lead to biodiversity loss, economic insecurity, instability and conflict, often followed by displacement of people and changes in occupancy and migration patterns (Barnett, 2003).

2. EFFECTS OF CLIMATE CHANGE ON HIMALAYAN GLACIERS

In response to increasing temperatures over the past 100 years, mountain glaciers have thinned, lost mass and retreated (IPCC, 2001). Although other factors, like precipitation and cloud cover, also affect the retreat of glaciers, air temperature is widely considered to be the most important factor (IPCC, 2007). Even in areas where precipitation is expected to increase, changes in temperatures are expected to dominate and glaciers are expected to shrink. Studies related to changes in mass balance under changed climatic scenarios have shown significant changes towards the losses in glacier mass (Kulkarni *et al*., 2003).

Considering the physiographic settings of peninsular and extra peninsular regions of India, the two regions are likely to react to climate change in different ways for their contrasting hydrological conditions. The Greater Himalayan region, also known as the Water Tower of Asia, covers approximately 7 million km^2 area of highly heterogeneous geography with great climatic variability and forms a barrier to atmospheric circulation (Xu *et al.*, 2007). The Greater Himalayas hold the largest mass of ice outside Polar Regions and are the source of the ten largest rivers in Asia. The high Himalayan and Inner Asian ranges have 116,180 km^2 of glacial ice, the largest area outside polar regions (Owen *et al.*, 2002; Li *et al.*, 2008).

The discharge of rivers which originates in Himalaya has contributions from snowmelts, glacier melts and surface runoff due to liquid precipitation in their catchment areas besides influx of groundwater. Average water yield per unit area of the Himalayan rivers is almost double that of the south peninsular river systems, which indicates the importance of snow and glacier melt contribution from high mountains (Kumar *et al.*, 2005).

Throughout the Greater Himalayas, water melts from permanent snow and ice and from seasonal snow packs and is stored in high-elevation wetlands and lakes. Melting occurs mainly in the summer, but when this coincides with the monsoon, it may not be as critical for water supply as melting in the spring and autumn shoulder seasons. When the monsoon is weak, delayed, or fails to materialize, melted water from snow and ice limits or averts catastrophic drought (Meehl, 1997). The contribution of snow and glacial melt to the major rivers in the region varies between 5% to 45% of the average flows (Xu *et al.*, 2007). Melting snow and ice contribute about 70% of the summer flow in the main Ganges, Indus, Tarim, and Kabul Rivers during the shoulder seasons (i.e., before and after precipitation from the summer monsoon) (Singh & Bengtsson, 2004; Barnett *et al.*, 2005).

Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74 °C over the last 100 years (IPCC, 2007). In many areas, a greater proportion of total precipitation appears to be falling as rain than before. During the last few decades, the Greater Himalayas have experienced increasing and decreasing precipitation trends (Shrestha *et al.*, 2000; Xu *et al.*, 2007; Ma *et al.*, 2009). Monsoon patterns have shifted, but the picture remains ambiguous (Shrestha *et al.*, 2000). The IPCC predicts that average annual precipitation will increase by 10-30% on the Tibetan Plateau as a whole by 2080, although rising evapotranspiration rates may dampen this effect (IPCC, 2007). As a result of climate change, snowmelt begins earlier and winter is shorter; this affects river regimes, natural hazards, water supplies, and people's livelihoods and infrastructure (Mall, 2006).

Progressively higher warming with higher altitude is a phenomenon prevalent over the whole of the greater Himalayan region. During the twentieth century, majority of the Himalayan glaciers have shown recession in their frontal parts, besides thinning of the ice mass as revealed by mass balance and secular movement studies undertaken by Geological Survey of India (Pandey, 2011). Himalayan glaciers are receding faster today than the world average (Dyurgerov and Meier, 2005). In the last half of the 20th Century, 82% of the glaciers in western China have retreated (Liu et al. 2006). On the Tibetan Plateau, the glacial area has decreased by 4.5% over the last twenty years and by 7% over the last forty years (CNCCC, 2007), indicating an increased retreat rate (Ren et al., 2003).

Glacier retreat in the Himalayas results from "precipitation decrease in combination with temperature increase. The glacier shrinkage will speed up if the climatic warming and drying continues" (Ren et al., 2003). Systematic study of glacier recession and mass balance of glaciers also reveal that though the retreat has increased over last few decades, the situation is not as alarming as being brought out by some experts. Figure 1 shows the Himalayan glacier retreat and Figure 2 shows the retreat of Gangotri Glacier.

Earlier studies on selected glaciers of Indian Himalaya indicate that most of the glaciers are retreating discontinuously since post-glacial time. Of these, the Siachen and Pindari Glaciers retreated at a rate of 31.5 meter and 23.5 meter per year respectively (Vohra, 1981). Gangotri Glacier is retreating at an average rate of 18 meter per year (Thakur et al., 1991). Shukla and Siddiqui (1999) observed the Milam Glacier in the Kumaon Himalaya and estimated that the ice retreated at an average rate of 9.1 meter per year between 1901 and 1997. Dobhal et al. (1999) surveyed the shifting of snout of Dokriani Bamak Glacier in the Garhwal Himalaya and found 586 meter retreat during the period 1962 to 1997.

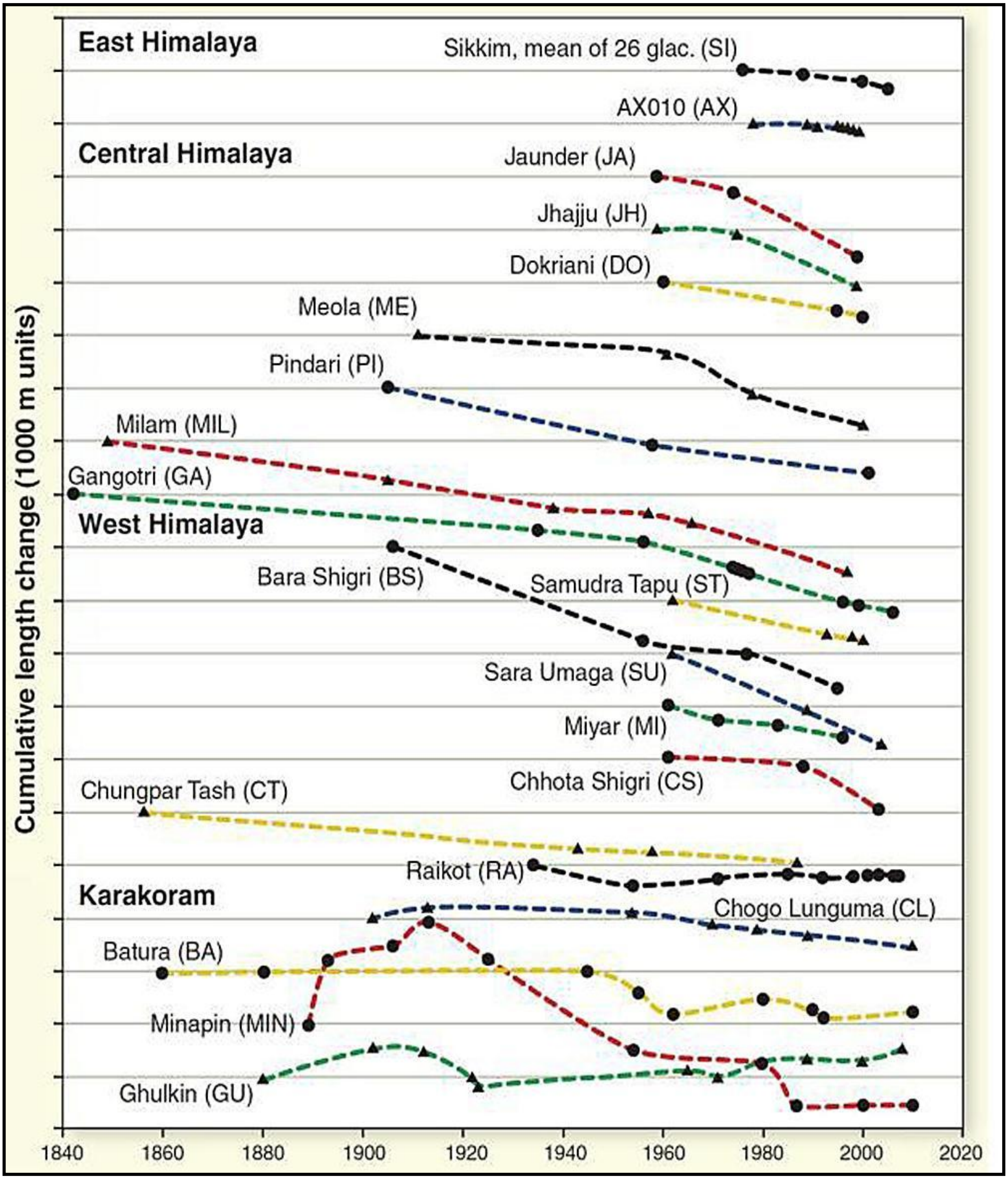

Figure 1. Most of the Himalayan glaciers show retreat since the mid-19th century, except the glaciers at Nanga Parbat in the northwest (RA, CL) and glaciers in the Karakoram, which show a complex behaviour (Bolch et al., 2012).

Figure 2. Evidence of Gangotri glacier retreat. (Image source: NASA Earth Observatory, Jesse Allen)

The average retreat was 16.5 meter per year. Matny found Dokriani Bamak Glacier retreated by 20 meter in 1998, compared to an average retreat of 16.5m over the previous thirtyfive years. (Matny, L., 2000). Geological Survey of India (Vohra, 1981) studied the Gara, Gor Garang, Shaune Garang, Nagpo Tokpo Glaciers of Satluj River Basin and observed an average retreat of 4.22 - 6.8 meter/year. The Bara Shigri, Chhota Shigri, Miyar, Hamtah, Nagpo Tokpo, Triloknath and Sonapani Glaciers in Chenab River Basin retreated at the rate of 6.81 to 29.78 meter/year. The highest and lowest retreat was observed in the Bara Shigri Glacier and Chhota Shigri Glacier respectively. During the period 1963 -1997, Kulkarni and others found the retreat of Janapa Glacier by 696 meter, Jorya Garang by 425 meter, Naradu Garang by 550 meter, Bilare Bange by 90 meter, Karu Garang by 800 meter and Baspa Bamak by 380 meter (Kulkarni et al., 2004). They further observed a massive glacial retreat of 6.8 km. (178 meter/year) in Parbati Glacier in Kullu District during 1962 to 2000. In their studies they observed an overall 19% retreated in glaciated area and 23% in glacier volume in last 39 years.

Gangotri glacier, the source of sacred river Ganga, is under observation by GSI since 1935. The records showed that the annual retreat has varied between 10 and 38 meters. The analysis of the retreat data, in terms of the retreat length versus total length of the glacier during 1956-96 indicates that the glacier has annually lost about 0.093% of its total length of about 30 km (Singhal, 2001). If current warming continues, glaciers located on the Tibetan Plateau are likely to shrink from 500,000 km^2 (the 1995 baseline) to 100,000 km^2 or less by the year 2035 (IPCC, 2007; Ye & Yao 2008).

Some studies, such as the following, even showed that flows into some basins are mostly driven by precipitation:

1. Runoff due to glacial melt is minor in the wetter monsoon catchments of the Ganges and Brahmaputra but more substantial in the drier westerly-dominated headwaters of the Indus (Immerzeel et al., 2010; Kaser et al., 2010).

2. In glaciated regions with winter accumulation, where an earlier peak of spring snowmelt is expected, the monsoon-influenced catchments will maintain peak discharge in summer even with significant reduction in glacier size (Immerzeel et al., 2010; Kaser et al., 2010).

3. Inter-annual runoff variation in the Himalayan glacier catchment is driven more by precipitation than by the mass balance change of glaciers (Thayyen and Gergan, 2010).

4. In the Dokriani glacier, winter snowfall has a more pronounced effect on headwater runoff variability than the variation produced by runoff from a receding glacier (Thayyen et al, 2010).

Most of the glacial lakes in the Himalayan region are known to have formed within the last 5 decades, and a number of Glacial Lake Outburst Flood (GLOF) events have been reported in this region. At least between 3 to 10 years one GLOF event was recorded in Himalayan region. These GLOF events have resulted in loss of many lives, as well as the destruction of houses, bridges, fields, forests and roads. GLOFs exacerbate land degradation, increase variations in the hydrological regime, degrade biodiversity, and trigger many socioeconomic externalities.

As global warming and climate change continue to increase the atmospheric temperature, it will lead to a continuous shift of zero temperature line (snow line) toward higher altitude. Thus glaciers will receive more liquid precipitation and less monsoonal solid precipitation. Shift in snowline will result in lesser input to glacier mass balance during summer periods. Therefore, higher atmosphere temperature and more liquid precipitation at higher altitude in the Himalayas will lead to rapid retreat of glaciers and downstream flooding in the coming future (Hasnain 2002, Kadota *et al.* 1993).

Retreat in glaciers can destabilize surrounding slopes and may give rise to catastrophic landslides (Ballantyne and Benn, 1994; Dadson and Church, 2005), which can sometimes lead to outbreak floods. Excessive meltwaters, often in combination with liquid precipitation, may trigger flash floods or debris flows (IPCC, 2007). Initially, increased melting will result in increased discharge. With time, however, as glaciers completely disappear or approach new equilibrium, long-term effects will be increasing water shortages and limited supplies for downstream communities, particularly during the dry season. Indus, Ganges and Brahmaputra rivers depend on around 16000 Himalayan glaciers for the source of water (IPCC, 2007).

Loss of ice reserves may result on the reduced water availability in the rivers of Indus – Ganga plains, especially in dry season that may adversely affect the population settled in the Indo-Gangetic plains on northern states (Gosain and Rao, 2004). Given that some 22% of all people on Earth are sustained by Asia's Water Tower, the cascading effect of most concern is the impact of increased temperatures and reduced water supplies on downstream food production (Xu *et al.*, 2009). Rees and Collins (2006) show that if all the Himalayan glaciers were to disappear, there would be about a 33 per cent reduction in annual mean flow in the west compared to the 1990 level, whereas the decline in the east would be only about 4-18 per cent.

Though glacial sources make Indus-Ganga-Brahmaputra river systems perennial, monsoonal rainfall is primarily responsible for their large annual volume. More intense rainfall concentrated over a few days along with large glacial melt will increase the chances of flash floods in the river basins in short term.

Rising temperatures are also affecting the permafrost layer in the Himalayas. The deterioration of the permafrost layer will have impacts on slope stability, erosion processes, hydrology and the ecology, with subsequent implications for people depending on these areas for their livelihoods (Lawrence and Slater, 2005).

The Greater Himalayas are also an important carbon sink. It was seen that the organic carbon content of soils subtending grasslands on the Qinghai–Tibetan Plateau composes about 2.5% of the global pool of soil carbon (Wang *et al.*, 2002). Projected shifts in Tibetan Plateau ecosystems, from alpine steppe and desert to alpine meadow and shrublands, may cause the near-complete disappearance of permafrost with the potential cascading effect of releasing most of the region's soil carbon (Ni, 2003; Anismov, 2007; Wilkes, 2008). No model exists yet that captures the interactions of the critical variables like melting Himalayan glaciers, degraded permafrost and wetlands, shifting alpine ecosystems, and changes in monsoon climates.

The cascading effects of rising temperatures and loss of ice and snow in the Himalayan region are affecting water availability (amounts, seasonality), biodiversity (endemic species, predator–prey relations), ecosystem boundary shifts (tree-line movements, high-elevation ecosystem changes), and global feedbacks (monsoonal shifts, loss of soil carbon) (Xu *et al.*, 2009). The IPCC report of 2007 estimated that accelerated melting of the Himalayan ice caps and the resulting rise in sea levels can increase the frequency of floods in the short-term during the rainy season and can greatly magnify the impact of tidal storm during the cyclone season. Glaciations and snow cover at low latitudes can play an important role in Earth's radiation budget as well. In summer, the vast highlands in Asia heat up more than the Indian Ocean, leading to a pressure gradient and a flow of air and moisture from the ocean intensifying the Indian monsoon (Qiu, 2008). This pressure gradient may be changing due to loss of glacial and snow cover in the Greater Himalayas. Loss of Greater Himalayan ice and snow will have still unknown cascading effects on global sea-level rise.

3. EFFECTS OF CLIMATE CHANGE ON SEA LEVEL RISE IN INDIA

There are two ways in which climate change and global warming can cause sea levels to rise are: (a) thermal expansion and (b) the melting of glaciers, ice caps etc. Global warming or increases cause the oceans to warm and expand in volume inducing a rise in the sea levels. Furthermore, warmer climate facilitates melting of glaciers, ice caps and ice sheets causing further addition of water to the oceans. In fact, the major cause of sea level rise is the thermal expansion of the oceans which contributes substantially in recent time (1993-2003) (IPCC, 2007). A sea-level rise of just 400 mm. in the Bay of Bengal would put 11 percent of the Bangladesh's coastal land under water, and can create 7 to 10 million "climate refugees" (IPCC, 2007). Thousands of water supply wells in these areas that supply fresh water to approximately 17 million people will be adversely affected by this incidence.

The *Sundarban*s, one of the significant mangrove ecosystems of the world, is already affected by climate change. Recent report suggests that 45 cm. rise in sea level (likely by the end of the 21st century), combined with other forms of anthropogenic stress on the *Sundarbans*, could destroy 75% of the *Sundarbans* mangroves (IPCC, 2007). Already, *Lohachara* Island and New Moore Island/South *Talpatti* Island have disappeared under the sea, and *Ghoramara* Island is half submerged (Douglas, 1997).

According to a study, the surface water temperature has been rising at the rate of 0.5 ^{o}C per decade over the past three decades in the *Sundarbans*, eight times the rate of global warming rate of 0.06 degree Celsius per decade that makes the *Sundarbans* one of the worst climate change hotspots (Mitra et al. 2009). The study found a change of 1.5 ^{o}C from 1980 to 2007, which is a major threat to the survival of flora and fauna in this ecosystem. *Sundarbans* are getting continuously affected from increasing salinity and extreme weather events like tropical cyclones.

Some researchers predict that the dying of the upper portions of the *Sundari* trees is likely to be the consequence of slow increase of salinity over a long period of time. Global warming will accelerate the process of erosion in coastal and estuarine zones either through increased summer flow from the glaciers or by increased tide penetration due to sea level rise (IPCC, 2007). Erosion and sedimentation processes, along with subsequent churning action, increase the saturation of suspended solids, thus can decrease the transparency. The reduced transparency affects the growth and survival of phytoplanktons that produce 75% of the earth's oxygen supply. Damage to this community may adversely affect the food chain in this mangrove-dominated deltaic complex, which is the nursery and breeding ground of aquatic lives. There was a rising trend in the sea level at Mumbai (Bombay) during 1940-86 and Chennai (Madras) during 1910-33 (Das and Radhakrishnan, 1991). A rise of sea level by 0.08 meter with a corresponding fall in the pressure was confirmed during 1901-40 as per the studies on the atmospheric and tide gauge data (Srivastava and Balkrishnan, 1993).

4. CLIMATE CHANGE, SALINITY INGRESSION AND GROUNDWATER DEPLETION

A warmer climate will accelerate the hydrological cycle; can alter the intensity and timing of rainfall. Warm air can hold more moisture and can increase evaporation of surface moisture, which in turn can intensify rainfall and snowfall events. So, intensity of flood will also increase. On the other hand, higher temperature can also increase higher evaporation and plant transpiration rates and hence, more drying up of soils. This will entail higher losses of soil moisture and groundwater recharge and greater exposure to desertification and soil erosion. All these will have negative impacts on the integrity of groundwater recharge systems. If there is deficiency of moisture in the soil, solar radiation will increase the temperature, which could contribute to longer and more severe droughts (Trenberth,1999).

Besides being the chief determinant of economic welfare of India, the summer monsoon is the predominant source of fresh water required for the rejuvenation of the water resources after the hot pre–monsoon spell. The prime concern today is the probable impacts that climate change and global warming might have on the annual cycle of the monsoon and the associated precipitation over south Asia.

Changes in the amounts or patterns of precipitation will change the route/ residence time of water in the watershed, thereby affecting its quality. As a result, regardless of quantity, water could become unsuitable as a resource if newly-acquired qualities make it unfit for the required use. For example, in areas with relatively high water tables, or under intensive irrigation, increased evaporation due to higher temperatures will raise the concentration of dissolved salts. Further, increased flooding could raise water tables to the point where agrochemicals/ industrial wastes from soil leach into the groundwater supply.

In a number of studies, it has been proved that global warming and decline in rainfall may reduce net recharge and can affect groundwater levels (IPCC, 2007). Decrease in winter precipitation would reduce the total seasonal precipitation being received during December–February, and can impose greater water stress. Intense rain for few days will result increased frequency of floods and the monsoon rain would also be lost as direct run-off, thus can decrease the groundwater recharging potential (Mall *et al*., 2006). Increased rainfall amounts and intensities will lead to greater rates of soil erosion. Rising sea levels will threaten coastal aquifers. Many of India's coastal aquifers are already experiencing salinity ingress including Saurashtra coast in Gujarat and Minjur aquifer in Tamil Nadu. Increasing frequency and intensity of droughts in the catchment area will lead to more serious and frequent salt-water intrusion in the estuary and thus can deteriorate surface and groundwater quality (Xu, 2003; Thanh *et al.*, 2004). Some scientists suggest that climate change may alter the physical characteristics of aquifers themselves. Higher CO_2 concentrations in the atmosphere may change carbonate dissolution and can promote the formation of crust, which in turn may negatively affect infiltration properties of the topsoil.

Problems in groundwater management in India have potentially huge implications due to global warming. The most optimistic assumption suggests that an average drop in groundwater level by one meter would increase India's total carbon emissions by over 1%, because the time of withdrawal of the same amount of water will increase fuel consumption. A more realistic assumption reflecting the area projected to be irrigated by groundwater in

2003, suggests that the increase in carbon emission could be 4.8% for each meter drop in groundwater levels (Mall et al., 2006).

5. EFFECTS OF CLIMATE CHANGE ON INDIAN RIVER BASINS

The changes in the hydrological response of a river basin will depend on the sources of runoff, climatic conditions, physical characteristics of the basin and the magnitude of projected climatic scenarios. Thus, basins located in different regions will experience different impact of the variability in the climate.

In the Himalayan region, a variety of basins exist and broadly, in the terms of source of runoff, these can be categorized in there types of basins:

(1) **Rain-fed basins:** Runoff is generated exclusively from rainfall; the altitude of such basins varies from about 500 to 2000 m.

(2) **Snow-fed basins:** Runoff is generated both from rainfall–runoff and snowmelt; the altitude varies from 2000 to about 4000 m. The contribution from snowmelt increases with altitude. The precipitation and temperature patterns in this type of basins are such that snowfall occurring during the preceding winter is completely melted away during next spring and summer months, i.e. such basins receive seasonal snow.

(3) **Glacier-fed basins:** Runoff from such basins is primarily generated from the melting of permanent snow fields and glaciers. Direct rainfall contribution is not significant. These are high altitude basins and cover an elevation range about 4000 to 6000-7000 m (Singh and Bengtsson, 2004).

All the 20 river basins in India are different from each other in terms of spatial and temporal water resources availability; topography; geomorphological characteristics; meteorological behaviors etc. During different times in the past, different rivers changed their course a number of times. Climate change can bring significant changes in these basins along with adverse socio-economic consequences.

The quantity of surface run-off due to climate change would vary across the river basins as well as sub-basins in India (Gosain and Rao, 2004). However, there is general reduction in the quantity of the available run-off. The Indus basin is endowed with plenty of water resources particularly with the glacial wealth. The Himalayan Rivers generally carry high silt load and rivers in Indus basin is not an exception.

There is rising trend in temperature in the basin, however minimum temperature has shown falling trend (Gosain and Rao, 2004). The Ganga basin is richest basin in terms of availability of utilizable surface water resources and replenishable ground water resources. There is a rising trend in temperature in the basin except minimum temperature in monsoon period which is showing falling trend. Various studies conducted in the Ganga basin show similar type of findings as were recorded for Indus basin (Gosain and Rao, 2004).

Detailed work has been carried out on the river basin-wise assessment of temperature variability and trends in the northwest and central India. A higher rate of warming or cooling has been observed in some pockets in a large basin like Ganga. The trends of changes in temperature suggest that majority of the basins (7 river basins: Ganga, Indus-lower, Mahanadi, Mahi, Narmada, Brahamani & Subaranrekha, and Tapi) have experienced an increasing trend in mean annual temperature over the last century, while 2 basins (Sabarmati and Luni & other small rivers) have experienced cooling trends. For the warmer basins the range of increase in mean annual temperature varied between 0.40 to 0.64 °C per 100 years and for the cooler basins it varied between –0.15 to -0.44 ° C per 100 years. A comparison of magnitude of warming and cooling trends of different river basins indicates that Narmada basin experienced maximum warming as compared to other basins, while Sabarmati river basin has shown the largest cooling trend (Ministry of water resources, 2008).

Changes in rainfall and relative humidity in different river basins in the northwest and central India also showed an interesting trend in a study. The seasonal and annual trend of changes in rainfall, rainy days, heaviest rain and relative humidity has been studied over the last century for nine different river basins in the northwest and central India. Majority of river basins have shown increasing trend both in annual rainfall and relative humidity. The magnitude of increased rainfall for considered river basins varied from 2 to 19% of mean per 100 years. Maximum increase in rainfall is observed in the Indus (lower) followed by the Tapi river basin. Most of the river basins have experienced decreasing trend in annual rainy days with maximum decrease in the Mahanadi basin.

The heaviest rain of the year has increased by 9 to 27 mm. per 100 years over different river basins, being maximum increase for Brahamani & Subaranrekha river basin. A combination of increase in heaviest rainfall and reduction in the number of rainy days indicated the possibility of increasing the severity of floods. Ganga, Narmada, Godavari, Krishna and West Coast indicate a falling trend in the annual rainfall of varying magnitude. Such information is very useful for the planning, development and management of water resources in the study area (Ministry of water resources, 2008).

The projected scenarios for rainfall over India for different seasons are variable as well. The increase in annual mean precipitation over the India is projected to be 7 to 10% by 2080s. Winter precipitation may decrease by 5 to 25%. An increase of 10 to 15% is projected in area-average summer monsoon rainfall over the India. Over northwest India, during monsoon season an increase of about 30% or more is suggested by 2050s (Ministry of water resources, 2008). The western semiarid margins of India could receive higher than normal rainfall in the warmer atmosphere. It is likely that date of onset of summer monsoon over India could become more variable in future. IPCC (2001) has indicated that variability in Asian summer monsoon is expected to increase along with changes in the frequency and intensity of extreme climate events in this region. All climate models simulate an enhanced hydrological cycle and increases in annual mean rainfall over South Asia.

Gosain and Rao (2003) showed that the quantity of surface run-off due to climate change would vary across the river basins as well as sub-basins in India. However, there is general reduction in the quantity of the available run-off. An increase in precipitation in the Mahanadi, Brahimani, Ganga, Godavari and Cauvery is projected under climate change scenario; however, the corresponding total run-off for all these basins does not increase.

Spiti River, a high altitude Himalayan river located in the western Himalayan region, the annual snowmelt run-off, glacier melt run-off and total stream flow increase linearly with increase in temperature, but the most prominent effect of temperature increase has been noticed on glacier melt run-off (Singh and Kumar, 1997). River basins of Mahi, Pennar, Sabarmati and Tapi shall face water shortage conditions. On the other hand, river basins belonging to Godavari, Brahmani and Mahanadi shall not face water shortages, but severity of flood shall increase in these areas (Gosain and Rao, 2004). A change in field-level climate may alter the need and timing of irrigation. In India, roughly 52% of irrigation is dependent on groundwater use. So, it can be an alarming situation with decline in groundwater and increase in irrigation requirements due to climate change (Mall *et al*., 2006).

By the mid of the 21st century, annual average river runoff and water availability will increase by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics, some of which are presently water-stressed zones (Trenberth, 1999). There will be an increase in drought affected areas and the frequency of heavy precipitation will increase, which, in turn, will increase flood risk.

Since many rivers are already under a great deal of stress due to excessive water withdrawal or land development, and this stress may be exacerbated by changes in climate, anticipating and planning adaptive strategies may be critical. The identification and prioritization of actions that can be taken now to enhance the resilience of riverine ecosystems in the face of disturbance may minimize impacts, such as biodiversity loss or severe flooding. Higher resolution climate change forecasts for specific basins or sub-basins and strategies developed within the context of local economies and societal needs are vital in order to fully develop and implement site-specific action plans. Proactive measures that restore the natural capacity of rivers to buffer climate change impacts are obviously the most desirable actions, since they may also lead to environmental benefits, such as higher water quality and restored fish populations. Delays in the implementation of proactive forms of restoration, rehabilitation, and river management will inevitably exacerbate the effects of global climate change on efforts to balance the needs of humans and rivers.

6. CLIMATE CHANGE, WATER RESOURCES AND HEALTH

Clearly, the health implications of changes to water supply are far-reaching. Currently, more than 3 million people die each year from avoidable water-related disease,30 most of whom are in developing countries. The effects of climate change on water will exacerbate the existing implications of water shortages on human health, as follows:

- **Water-borne diseases:** Those result from the contamination of water by human/ animal faeces, or by urine infected with pathogenic viruses/ bacteria, both of which are more likely to occur during periods of flood and therefore intensify with the projected increases in natural disasters under climate change. Diseases are transmitted directly when the water is drunk or used in food preparation.

- **Water-washed diseases:** Those resulting from inadequate personal hygiene as a result of scarcity or inaccessibility of water (including many water-borne diseases and typhus).

- **Water-based diseases:** Those caused by parasites that use intermediate hosts living in/near water (e.g. guinea worm).

- **Water-related diseases:** borne by insect vectors that have habitats in/near water (such as malaria). For example, malaria has recently appeared in Nairobi and the highlands of Kenya, illustrating the expanding range of mosquitoes due to warmer temperatures.

• **Water-dispersed diseases:** infections for which the agents proliferate in fresh water and enter the human body through the respiratory tract (e.g. legionella). (Kabat et al, 2015).

7. CONCLUSIONS

Climate change would significantly affect the temporal and spatial availability of the water resources in the country. It may lead to the re-allocation of the water for meeting the demands of the different sectors. As the climate change may change the rainfall characteristics in time and space, the surface runoff and rainfall recharge to the groundwater would also be significantly affected. Furthermore, because of adaptation in other sectors due to climate change; there may be other physical changes in the basin which would influence the hydrological cycle considerably. Thus, the methodologies for the assessment of surface water as well as Groundwater resources are required to be modified considering all the changes expected in the basin because of climate change.

Humans and human civilizations have developed at a time in the earth's history when climate, in a geological sense, has been relatively stable, and that stability has been a major factor in the evolution and development of our society. Now the stability has been affected and we should recognize the harmful effects of anthropogenic activities, which have the potential to change our climate. The impact of climate change on the various components of water budget of the planet earth needs to be understood properly before formulating adaptation and mitigation strategies. All the information and knowledge of snow, ice and glaciers of Himalaya, groundwater resources of peninsular and extra-peninsular regions including recharge processes, soil moisture retention and evaporation, sea level changes and coastal process etc. have to be integrated for creating a sustainable condition.

Steps should be taken to understand the food, water and energy security implications for the people living in the basins who depend directly on melt water, either seasonally or as an overall component of their water budget, and how they are affected by climate change in their mountainous environment. Sustainable water and land management strategies, coastal zone management strategies and hydrological design management methods should be modified and applied in a sustainable manner to stabilize the equilibrium of the systems.

In addition, increased and widespread hydrologic monitoring systems are needed across the country. There should also be a systematic reexamination of engineering design criteria and operating rules of existing dams and reservoirs under conditions of climate change. The decision–making bodies on water policies in India must realize that climate is not static, and assumptions made about the future based on the climate in the past may be inappropriate. Assumptions about the probability, frequency, and severity of extreme events used for planning should be carefully reevaluated. Studies are required to ascertain the impacts at local scales by using sufficient and reliable database. These studies are still in infancy and a lot more data both in terms of field information is to be generated. The impact of future climatic change may be felt more severely in developing countries such as India whose economy is largely dependent on agriculture and is already under stress due to current population increase and associated demands for energy, fresh water and food. It is absolutely essential for us to secure the right for saving water resources and environment in general. Though a lot of regulations, acts and laws have been enacted here and there, but it is more important to raise the general awareness of the common people. We have to think together in a sustainable manner to ensure a healthy earth, both in social and in biological dimensions.

Table 1. Climate change impact on water and health of four major regions of India in 2030s; *Indian Network for Climate Change Assessment Report* (Manoj, K., Kumar, P.P., 2013).

Regions	Effects on water resources
Himalayan Regions	1. Water yield (mainly covered by the river Indus), is expected to increase by 5-20% in most of the areas. 2. Expected increase in yield up to 50% in specific areas of Jammu and Kashmir and Uttarakhand. 3. Increase in rain intensity by 2-12%. 4. Enhanced evapo-transpiration. 5. Increased glacier melt. 6. Flash floods causing large scale landslides, leading to loss of agricultural area affecting food production and security.
North-eastern Regions	1. Precipitation trend exhibits considerable spatial variability in water yield. 2. Northern parts of the region demonstrate a decline in precipitation varying from 3% in the north-western part (of the North-East) to about 12% in the north-eastern part. 3. The central part displays an increase in precipitation which varies from 0% to 25%. 4. Major portions of the North-Eastern region (except some parts of Mizoram, Tripura, Manipur and Assam) depicts an increase in evapo-transpiration in the 2030s. 5. Reduction in water yield for the Arunachal Pradesh by up to about 20% and increased evapo-transpiration. 6. Assam and Manipur can demonstrate increase in water yield up to about 40%. 7. Overall change: decline in winter precipitation, increased summer precipitation intensity leading to increase runoff and landslides. 8. High night temperatures can affect paddy cultivation as evapo-transpiration will increase. 9. Soil erosion can affect tea plantations. 10. Decrease in food production in winters.
Western Ghats	1. The region exhibits wide variability in water yield. 2. Northern portion displays a drop in the water yield varying from 10% to 50%. 3. The central portion shows an increase in water yield ranging from 5%

	to 20%. 4. The southern parts of Karnataka and Kerala demonstrate a reduction in water yield up to 10%. 5. Cash crops can be affected adversely. 6. Large scale flooding and soil erosion can occur.
Coastal Regions	1. Eastern coastal parts of West Bengal, Orissa and the northern coastal parts of Andhra Pradesh display a drop in water yield as less as 40%. 2. Southern parts of Andhra Pradesh and northern parts of Tamil Nadu can indicate growth in water yield by 10% to 40%. 3. The western coastal region demonstrates overall reduction in water yield varying from 1% to 50% (except, in the coast along Karnataka, where an increase of 10% to 20% is projected). 4. Southern tip of the coastal region indicates no change in water yield. 5. Rise in sea level can cause incursion of coastal waters leading to increase in salinity affecting fresh water availability for drinking and agriculture. 6. Productivity and distribution of marine as well as fresh water fisheries can be affected.

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