Impact of Climate Change on Water Resources and Glacier Melt and Potential Adaptations for Indian Agriculture*

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In Asia, more than a billion people could be affected by a decline in the availability of freshwater, particularly in large river basins, by 2050. Glacier melt in the Himalayas, which is projected to increase flooding and rock avalanches, will affect water resources in the next two to three decades. As glaciers recede, river flows will decrease. Coastal areas, especially heavily populated mega-delta regions, will be at greatest risk due to increased flooding from the sea and, in some cases, from river flooding.

India is one of the more vulnerable and risk-prone countries in the world. Over the centuries, its population has learned to cope with a wide range of natural and human-made hazards. Rapid population growth, high densities, and poverty have led to an increase in vulnerability over the last few decades. Climate change is expected to increase the frequency and intensity of current hazards and the probability of extreme events and new vulnerabilities with differential spatial and socioeconomic impacts. This is expected to further degrade the resilience of poor, vulnerable communities. It is therefore important to understand a number of processes that are rapidly changing India's landscape, altering livelihood opportunities and wealth distribution, which in turn affect the vulnerability of many communities and stakeholders and their capacity to adapt to long-term risks.

India faces a turbulent water future. The country has a highly seasonal pattern of rainfall, with 50% of precipitation falling in just 15 days and over 90% of river flows occurring in just four months. The Indian mainland is drained by 15 major (drainage basin area >20,000 km2), 45 medium (2,000 to 20,000 km2) and over 120 minor (<2,000 km2) rivers, besides numerous ephemeral streams in the western arid region. The Himalayan glaciers feed India's most important rivers. But rising temperatures means that many of the Himalayan glaciers are melting fast, and could diminish significantly over the coming decades with catastrophic results. In the long run, the water flow in the Ganges could drop by two-thirds, affecting more than 400 million people who depend on it for drinking water. In the short term, the rapid melting of ice high up in the Himalayas might cause river swelling and floods. The formation of glacial lakes of melt-water creates the threat of outburst floods leading to devastation in lowland valleys.

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According to a report by the Intergovernmental Panel on Climate Change looking at the threat from climate change to human development and the environment, “only the polar icecaps hold more fresh water than the Himalayan glaciers”: “If the current trends of climate change continue, by 2030 the size of the glaciers could be reduced by as much as 80 per cent,” (“Up in Smoke -- Asia and the Pacific”)

The adverse impact of climate changes includes water crisis and an increased risk of extinction for an estimated 20 to 30 per cent of plant and animal species in India if the global average temperature exceeds 1.5 to 2.5 degrees Celsius. Climate change will also significantly impact health in India. The most vulnerable will be the poor, the disabled, the youngest and oldest members of the population as they already face limited access to health facilities and have limited disposable income to cover additional medical costs.

The **Ganges river basin** runs from the central Himalayas to the Bay of Bengal, and covers parts of Nepal, India, China and Bangladesh. The basin occupies 30% of the land area of India and is heavily populated, increasing in population density downstream to Bangladesh, the most densely populated country in the world (WRI, 2003; Rashid & Kabir, 1998). Water withdrawal poses a serious threat to the Ganges. In India, barrages control all of the tributaries to the Ganges and divert roughly 60% of river flow to large scale irrigation (Adel, 2001). India controls the flow of the Ganges into Bangladesh with over 30 upstream water diversions. The largest, the Farraka Barrage, 18 km from the border of Bangladesh, reduced the average monthly discharge of the Ganges from 2,213 m^3/s to a low of 316m^3/s [14%] (Goree, 2004; FAO, 1999).

Climate change will exacerbate the problems caused by water extraction. The Himalayan glaciers are estimated to supply 30-40% of the water in the Ganges, which is particularly critical in the dry season prior to the monsoon rains. The projected annual renewable water supply for 2025 indicates water scarcity (WWF, 2007). Although the Ganges catchment drains virtually all of the Nepal Himalayas and water supply per person in the basin ranges from adequate to ample, its dry season outflow (from December to February) to the sea is non-existent (Revenga et al., 2000). Overall, excessive water diversions threaten to eliminate natural flows and severely damage people’s livelihoods in the Ganges.

The **Indus river basin** spans parts of four countries (Afghanistan, Pakistan, India and China) in an area that is more than 30% arid, and much drier than the nearby Ganges river basin (WRI, 2003). The Indus River is critical for Pakistan’s 160 million people, and irrigates 80% of its 21.5 million ha of agricultural land (Rizvi, 2001). The watershed is also an area of rich biodiversity, particularly where it opens to the Arabian Sea. The Indus river delta is a highly productive area for freshwater fauna and an important region for water birds (Ramsar Convention on Wetlands, 2003).

The Indus River is extremely sensitive to climate change due to the high portion of its flow derived from glaciers (WWF, 2007). Temperature controls the rate of glacier melt, which in turn, provides more water in dry, warm years and less water in cool years. River catchments with a large portion of glacial melt water experience less variability in water flows. With climate warming, many glaciers will no longer exist to moderate the flow of these rivers. Thus communities which depend on glacier water will face more severe water shortages, variability and potentially greater flooding too (IPCC, 2001a; WWF, 2005g; Rizvi, 2001). The Himalayan glaciers provide the Indus with 70-80% of its water (Kiani, 2005), the highest proportion of any river in Asia. This is double the proportion of water that they provide the Ganges (30-40%). Himalayan glaciers provide 44.8% of the water in the Upper Indus in China alone (Yang, 1991).

The Indus basin is already suffering from severe water scarcity due to overextraction for agriculture, causing salt-water intrusion in the delta (WRI, 2003). In 1995, the Indus River already supplied much less water per person than the minimum recommended by the United Nations (UN) and by 2025 is predicted to suffer even more severe water scarcity (Revenga et al., 2000). Well-managed riparian forests are especially important in minimizing the impacts of climate change on river biota. They provide shade and temperature regulation, can moderate the effect of frequent, short duration storm events and can support natural water flow regimes. Climate change will exacerbate the impact of deforestation on water regulation. Although the Indus system is currently robust enough to cope with shortages of 10-13% in river flows, when the rivers flow drops to 15-20% below the average, irrigation shortages occur (Khan, 1999). Climate change will surely exacerbate the problems of irregular and low flow.

EVIDENCE OF CLIMATE CHANGES

Climate change will affect many sectors, including water resources, agriculture and food security, ecosystems and biodiversity, human health and coastal zones. Many environmental and developmental problems in Asia will be exacerbated by climate change. Under climate change, predicted rainfall increases over most of Asia, particularly during the summer monsoon, could increase flood-prone areas in East Asia, South Asia and Southeast Asia. Table 1 summarizes the impact and vulnerabilities to climate change in South Asia. In Central and South Asia, crop yields are predicted to fall by up to 30 per cent, creating a very high risk of hunger in several countries. Global warming is causing the melting of glaciers in the Himalayas. This means increased risk of flooding, erosion, mudslides and GLOF in Nepal, Bangladesh, Pakistan, and north India during the wet season. Because the melting of snow coincides with the summer monsoon season, any intensification of the monsoon and/or increase in melting is likely to contribute to flood disasters in Himalayan catchments. In the longer term, global warming could lead to a rise in the snowline and disappearance of many glaciers causing serious impacts on the populations relying on the 7 main rivers in Asia fed by melt water from the Himalayas. Throughout Asia one billion people could face water shortage leading to drought and land degradation by the 2050s (Christensen et al., 2007, Cruz et al., 2007). Projected sea level rise could flood the residence of millions of people living in the low lying areas of South Asia such as in Bangladesh and India (Stern, 2006, Cruz et al., 2007)

Table 1: Impacts and vulnerabilities to climate change in South Asia

Impacts	Sectoral Vulnerabilities
Temperature - Warming above the global mean temperature - Fewer very cold days **Precipitation, snow and ice** - Increase in precipitation in most of Asia. - Increase in the frequency of intense precipitation events in parts of South Asia - Increasing reduction in snow and ice in Himalayan and Tibetan Plateau glaciers **Extreme Events** Increasing frequency and intensity of extreme events particularly: - Droughts during the summer months and El Niño events; - Increase in extreme rainfall and winds associated with tropical cyclones; - Intense rainfall events causing landslides and severe floods; - Heat waves/hot spells in summer of longer duration, more intense and more frequent, particularly in East Asia.	**Water** - Increasing water stress to over a hundred million people due to decrease of freshwater availability, particularly in large river basins. - Increase in the number and severity of glacial melt-related floods, slope destabilization followed by decrease in river flows as glaciers disappear. **Agriculture and food security** - Decreases in crop yield for many parts of Asia putting many millions of people at risk from hunger. - Reduced soil moisture and evapotranspiration may increase land degradation and desertification. **Coastal Zones** - Tens of millions of people in lowland coastal areas affected by sea level rise and an increase in the intensity of tropical cyclones. - Coastal inundation is likely to seriously affect the aquaculture industry and infrastructure particularly in highly populated mega deltas. - Stability of wetlands, mangroves, and coral reefs increasingly threatened.

Temperature and Rainfall

Several studies predict changes in temperature and rainfall over the entire landscape of India and specifically for the western Himalayas and the Indo-Gangetic Plain Region (IGPR) during the last century. There is indication of increase in temperature and change in rainfall pattern during the 20th century (Table 2). Mirza et al. (1998) analyzed the trends and persistence in precipitation over Ganga basin. Time series of 10 meteorological station annual precipitations was examined for trends using the Mann-Kendall rank statistic, Student's f-test and regression analysis. Results indicate that precipitation in the Ganges basin is by-and-large stable. Precipitation in the Bangladesh part of the basin shows an increasing significant trend at the 95% confidence level.

Table 2: Change in temperature and rainfall pattern in India and part of IG Basin

Region	Temperature	Rainfall
All-India	• Increase in 0.4°C/100 yrs in mean annual temperature • Increase in maximum temperature (0.6°C/100 yrs) • General increase in the diurnal range of temperature	• Monsoon rainfall is trendless and is mainly random in nature over a long period. • Decadal departures in summer monsoon rainfall are found above and below the long-time average alternatively for three consecutive decades.
Western Himalayas	• Winter season – Srinagar, Mussoorie and Mukteswar show increasing trend (0.5°C/100 yrs) • Monsoon season – Srinagar, which is beyond the monsoon regime, shows significant increasing trend, whereas Mussoorie and Dehradun, which are at the foothills of the Himalayas, show decreasing trend.	• No increasing or decreasing trend for the last 100 years. • Western Himalayas gets more snowfall than eastern Himalayas during winter. • More rainfall in the eastern Himalayas than in the western Himalayas during monsoon season.
Indo-Gangetic Plain Region (IGPR)	• Annual surface air temperature of the IGPR shows rising trend (0.53°C/100 yrs during 1875–1958). • Decreasing trend (–0.93°C/100 yrs during 1958–1997).	• Summer monsoon rainfall over western IGPR shows increasing trend (170 mm/100 yrs) from 1900, while over central IGPR it shows decreasing trend (5 mm/100 yrs) from 1939 and over eastern IGPR a decreasing trend (50 mm/100 yrs) during 1900–84 and increasing trend (480 mm/100 yrs) during 1984–99. • Westward shift in rainfall activities over the IGPR.

(Mall et al., 2006)

Glacier/ice Melt

Glaciers throughout the world are in melt mode. Considered as the thermometer of global warming, world's best-known ice masses are fast disappearing (Figure 1). The mass balance of a glacier is the sum of all mass gains and losses during a hydrological year. Mean specific mass balance is the total mass balance divided by the total surface area of all glaciers and ice caps of a region, and it shows the strength of change in the respective region (Bates et al., 2008).

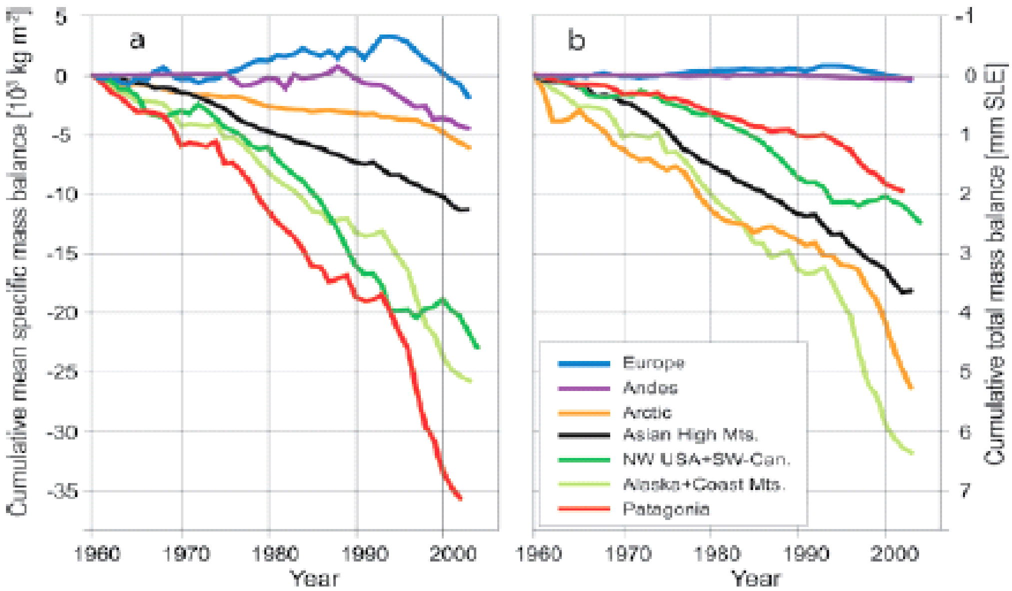

Figure 1: Cumulative mean specific mass balances (a) and cumulative total mass balances (b) of glaciers and ice caps, calculated for large regions (Dyurgerov and Meier, 2005).

Agencies conducting regular monitoring of several glaciers during the past 100 years in major basins of Himalayas from Shyok in the west to Changme Khangpu (Tista) in the East have revealed that a majority of the glaciers in the Himalayan region are passing through a phase of recession. The Gangotri glacier is shrinking — faster than ever before, faster every year. Recent investigations of the Gangotri glacier, which is at 3400 meters above sea level, have found the rate of retreat has almost doubled to 34m per year, compared to between 1935 and 1971 when it was retreating about 19 metres per year.

With the 27 km long Gangotri glacier shrinking, there is now less water downstream to dissolve the chemical wastes of over a 100 industries that pour into the river. With less water, the density of pollutants in the Ganga keeps increasing, making multi-crore projects like the Ganga Action Plan, totally ineffective. These glaciers are a primary source of water for 30 to 50 per cent of the major rivers in the Gangetic plain.

Recession may cause an increase in the discharge of Himalayan rivers due to enhanced melting, initially leading to a higher incidence of flooding and landslides. It spells disaster for areas dependent on perennial rivers like the Ganga. As the volume of ice diminishes, there will be no water left to flow in the river.

If the trend in glaciers retreat continues, a long-term loss of natural fresh water storage is predicted to be dramatic. As glaciers retreat, lakes commonly form behind the newly exposed terminal moraine. The rapid accumulation of water in these lakes can lead to a sudden breach of the moraine dam. The resultant rapid discharge of huge amounts of water and debris is known as a glacial lake outburst flood (GLOF) — and the results can be catastrophic to the downstream riparian area (Richardson and Reynolds 2000). Every country within the Himalayan region has at some time or other suffered a GLOF event. Records show 15 GLOF events recorded in Nepal, 6 in the Tibet Autonomous Region of China (with consequences for Nepal) and 5 in Bhutan.

Many studies have been carried out on the fluctuation of glaciers in the Indian Himalaya and significant changes (mostly retreats) have been recorded in the last three decades. The retreat of selected glaciers is summarised in Table 3. Most of these glaciers have been retreating discontinuously since the post-glacial period. Jeff Kargel of the USGS showed that the position of the Gangotri Glacier snout retreated about 2 km in the period from 1780 AD to 2001 (Figure 2) and is continuing to retreat. Almost all the glaciers of Himalaya and Karakoram are receding with varying rate. Gangotri glacier, source of river Ganga is receding at alarming rate, which has adverse impact in Himalayan Ganga basin.

Table 3: Retreat of glaciers in Himalaya and Karakoram

Mountain Range	Name of Glacier	Periods	Year	Total Retreat (metres)	Average Retreat (metre/ year)
Himalaya	Milam	1849-1957	108	1350	12.5
	Pindari	1845-1966	121	2840	23.5
	Shankulpa	1881-1957	76	518	6.8
	Poting	1906-1957	51	262	5.1
	Glacier No.3 in Arwa Valley	1932-1956	24	198	8.3
	Gangotri	**1934-1976**	**41**	**600**	**14.6**
		1962-2000	**38**	**1341**	**35.4**
	Zemu	1909-1965	56	440	7.9
		1975-1990	15	297	19.8
	Sonapani	1906-1963	57	905	15.9
Karakoram	Minapin	1906-1929	23	502	21.8
	Biafo	1861-1922	61	0	0
	Kichik Kumdan	1946-1958	12	1219	101.6
	Siachin	1929-1958	29	914	31.5
	Yengutsa	1892-1925	33	4134	125.3

Source: (Vohra, 1981) and (Bahadur, 2004)

Most of the Himalayan Ganga Basin is mountainous in nature and also glaciated (Table 4). Therefore, with changing climate these glaciated rivers can affect the downstream.

The Himalayan region is subject to significant and uncertain climate variability (Singh, 2004). The rate of retreat in recent times has, however, been much more rapid than the gradual retreat expected in an inter-glacial warming phase (Singh and Kumar, 2006). Thus, glaciologists and climatologists believe, is due to global warming.

Figure 2: Retreat of the Gangotri glacier snout during the last 220 years (from 1780 AD to 2001) (ICIMOD, (2007)

Table 4: Principal glacier-fed river systems of the Himalaya

River	Major River System	Mountain Area (km^2)	Glacier Area (km^2)	% Glaciation
Indus	Indus System	268842	7890	3.3
Jhelum		33670	170	5.0
Chenab		27195	2944	10.0
Ravi		8092	206	2.5
Sutlej		47915	1295	2.7
Beas		12504	638	4.4
Jamuna	Ganga System	11655	125	1.1
Ganga		23051	2312	10.0
Ramganga		6734	3	0.04
Kali		16317	997	6.01
Karnali		53354	1543	2.9
Gandar		37814	1845	4.9
Kosi		61901	1281	2.1
Tista	Brahmaputra System	12432	495	4.0
Raikad		26418	195	0.7
Nanas		31080	528	1.7
Subansiri		81130	725	4.0

Brahmaputra		256928	108	0.4
Dibang		12950	90	0.7
Lunit		20720	425	2.0

Source: Hasnain, 1999

Extreme Events - Floods and Droughts

Floods, droughts and cyclones are the key extreme climatic events in India. The total flood prone area in India is about 40 m ha (Mirza and Ericksen, 1996). Western parts of Rajasthan and the Kutchh region of Gujarat are chronically drought affected. Drought conditions have also been reported in Karnataka, Andhra Pradesh, Orissa and Bihar states (Sharma and Smakhtin, 2004). Drought disasters are more frequent during years following ENSO events. At least half of the severe failures of the Indian monsoon since 1871 have occurred during El Nino years (Webester et. al., 1998).

Droughts

The climate change risk to the Indian economy and its people is the increased intensity, frequency and geographical coverage of drought. Continuing severe climate change-induced drought that makes subsistence agriculture uneconomical in large parts of semi-arid central, western and southern India could catalyze a sharp increase in migration. Based on the rainfall deficiency for the last 100 years, on average 19% of the area and 12% of the population is annually affected by droughts in the north-western and southern states of the country. The primary impacts are reduced water availability for domestic, agriculture and livestock; low to failed agriculture production and reduced hydropower generation. This leads to reduced incomes for the people dependent on farming and livestock, dwindling fodder stocks, decline in nutrition and health status and increased incidences of debt. It also has impacts on the wider economy with the reduced availability of agricultural produce and constraints on power production.

Climate change is expected to increase the severity of drought, especially in western India where five river basins are expected to face acute to severe water shortages, impacting a large number of cities in Gujarat. The Ganga, Narmada, Krishna and Kaveri rivers are expected to experience seasonal or regular water stress, impacting western, northern and eastern India. Climate change is expected to increase drought in semi-arid peninsular and western India, forcing more of the landless and small and marginal farmers to migrate to cities. They often form the most vulnerable groups in cities – having limited skills, education, capital and access to the social networks that underpin much of economic and social mobility in urban India.

The most serious regional impact of climate change would be changes in the river hydrology in the Indo–Gangetic plain and the Brahmaputra valley. Four of the ten largest mega-urban regions of the twenty-first century, namely, Delhi, Dhaka, Kolkata and Karachi, lie on the banks of these great rivers along with more than 30 other million-plus cities. Significant changes in river hydrology and the availability of irrigation and drinking water could have a dramatic impact on the growth and development of the many small and medium-sized towns and million-cities that are expected to mushroom across these fertile plains in the next three decades, adding an unprecedented resource dimension to the social and economic transformation of northern and eastern India.

Floods

The main source of the datasets used in this study is from CRED for the past 48 years from 1960-2008, which is supplemented with data from some other sources. Although there are no standard criteria for selecting the flood events and defining their magnitudes for analysis, all the events considered here are only those that caused socio-economic damage and were reported. Table 5 represents the socio-economic damages caused due to flood events in South Asian countries. India is more vulnerable to flood compared to its neighboring countries followed by Bangladesh

Table 5: Socio-economic damages caused due to flood events in South Asian countries (1960-2008)

Damages	**Eastern Asia**	**Southeast Asia**	**South Asia**	**West Asia**
Events	290	397	559	102
Deaths	45,785	18,264	131,497	2,589
Total Population affected (million)	1680.5	93.0	1148.9	5.5
Estimated Cost (US$ billion)	170.34	11.60	55.35	4.60

Source: CRED International Disaster Database

Table 6 represents the socio-economic damages caused due to flood events in South Asian countries. India is more vulnerable to floods compared to neighboring countries followed by Bangladesh. Figure 3 shows the increasing trend in flood frequency in all the sub regions of Asia based on last 48 years datasets.

Table 6: Socio-economic damages caused due to flood events in South Asian countries

Damages	**Bangladesh**	**India**	**Nepal**	**Pakistan**	**Sri Lanka**
Deaths	52,033	55,656	5,637	8,877	1,050
Population affected (million)	304.63	763.99	2.98	37.69	7.96
Homeless	4219724	13210000	84925	4234415	2746601
Injured	102390	1561	1072	1981	1002
Estimated Cost (US$ ‘000)	12038400	29417188	977213	2865178	374364

Source: CRED International Disaster Database

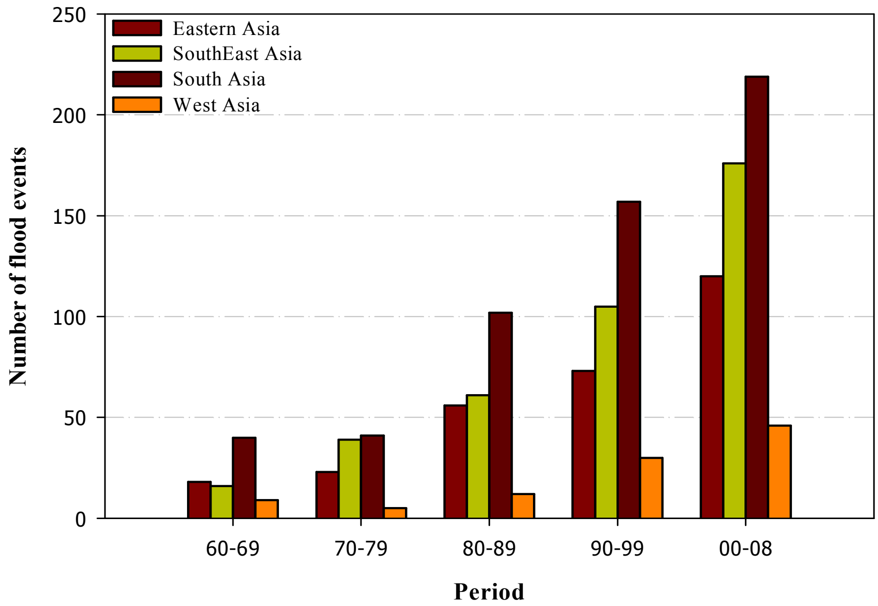

Figure 3: Flood disaster trend in Asia in the last 48 years

Increase in riverine and inland flooding, especially in northern and eastern India and adjoining Nepal and Bangladesh is also most important climate change risk. Tens of millions of people are currently affected by flood for three to six months of the year in eastern India. Increased precipitation and higher peak monsoon river flows due to glacial regression could exacerbate the situation for additional tens of millions. This is largely due to the high population densities across this region, combined with very high vulnerability due to a mix of poorly designed and executed flood management systems, complex land and water tenure regimes and high levels of poverty, which over the last few decades have severely degraded the coping capacity of millions of residents of eastern India. Climate change is expected to increase the severity of flooding in many Indian river basins, especially those of the Godavari and Mahanadi along the eastern coast. Floods are also expected to increase in northwestern India, adjoining Pakistan, and in most coastal plains, in spite of existing upstream dams and “multi-purpose” projects. Extreme precipitation is expected to increase substantially over a large area of the west coast and central India (Revi, A., 2008).

Sea Level Rise

Data over the last century indicate a mean sea-level rise (SLR) of less than one millimetre per year along the Indian coast. More recent observations suggest an SLR of 2.5 millimetres per year since the 1950s. An SLR of between 30 and 80 centimetres has been projected over the century along India’s coast, based on multiple climate change scenarios.

A World Bank-funded study uses multiple scenarios ranging from one to five metres of sea-level rise, based on evidence of increased rates of deglaciation in Greenland and Antarctica and the resultant increased probability of extreme climate scenarios. Up to one per cent of India's urban areas could be inundated by a three metre SLR, and just under two per cent with a five metre rise. A three-metre SLR is expected to affect more than one per cent of the population and a five metre rise, 2.5 per cent of the population. The overall regional compression of GDP as a result of losses directly due to SLR is estimated at 0.6 per cent from a one metre SLR, 1.6 per cent from a three metre SLR and 2.9 per cent from a five metre SLR for South Asia. The relative impact on India would typically be lower than in Bangladesh, where up to 10 per cent of the area and population are at high risk, but serious adaptation and mitigation measures will be required, especially for coastal cities and ports, which are expected to produce a high share of GDP and underpin India's growing manufacturing exports (Revi, A., 2008).

A second study, led by IIED, examined vulnerability within the Low Elevation Coastal Zone (LECZ) i.e. settlements and facilities at risk of a 10 metre SLR – probably the outer boundary of catastrophic climate change. It estimated that Asian countries contain three-quarters of the global LECZ population and two-thirds of the global LECZ urban population, with a higher concentration in cities over five million in size. India is estimated to have the second largest LECZ population, with about three per cent of national area at risk.

In short, SLR is a serious risk for a number of cities along India's coast. It is clearly in the national interest to invest in appropriate technology, in order to assess possible risks at various levels of climate change. The costs of inaction on this count alone could outstrip that investment by many orders of magnitude. The stretches along the western Indian coast that are most vulnerable to SLR are Khambhat and Kachchh in Gujarat, Mumbai and parts of the Konkan coast, and South Kerala. The deltas of the Ganga, Krishna, Godavari, Cauvery and Mahanadi on the east coast are expected to be lost, along with significant settlement areas and irrigated land and a number of urban settlements that are situated there. The loss of these important economic and cultural regions could have a considerable impact on the states of West Bengal, Orissa, Andhra Pradesh and Tamil Nadu. SLR, combined with an increased frequency and intensity of tropical cyclones, is expected to lead to an increase in extreme sea levels due to storm surge. The fact that India's coast, and especially its western seaboard and stretches along the Bay of Bengal, are expected to grow dramatically in terms of population, infrastructure and industrial investment in the next two decades implies a non-linear increase in coastal SLR vulnerability (Revi, A., 2008).

ADAPTATION AND MITIGATION MEASURES

In the context of climate change, mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Adaptation is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (UNFCCC).

Adaptation

- Glacial retreat and glacial lake floods are major problems linked to climate change in the Himalayas. There is need to enhance adaptive capacity in this region by strengthening disaster management capability, artificially lowering waters, and installing an early warning system with good communication system. There is a growing need to understand the life cycle of glaciers and their response to climate changes. To make it effective, a detailed database is required on seasonal and permanent ice cover, hydrology information with measurement of climatic variables.

- Proper information systems with sound techniques need to be developed and therefore research work must be taken up to identify the critical regions, which are at risks due to changing nature of climate.
- Identifying and using appropriate sectoral tools and an integrated assessment approach with adequate data inputs can lead to improved assessments with reduced uncertainties.
- Planners have to consider sea-level rise in the design of infrastructure in the coastal zone areas in prediction of future climate change,
- Information and means of improving adaptive capacity should provide to vulnerable communities i.e., improved conservation and management of water resources (supply-side and demand-side)
- Adaptation programmes should integrate climate component into Integrated Water Resources Management practices to reduce the impacts of extreme weather events on society and ecosystems. These programmes must help communities to assess risks and options to adapt to drought, coastal flooding and health risks.
- Involvement and participation of community at various levels of planning and management is a key to evaluate various coping options at local level.
- Early flood and drought warning system with good communication system
- Enhance technical and institutional capacity to understand, analyze and address climate change at various levels.

Mitigation

- Preventing and limiting the cause of climate change, by cutting back on production of greenhouse gases and planting more forests.
- Afforestation programme can help in controlling the phenomena of global warming and thus its devastating impacts in several ways. In Gangotri-Gaumukh region, afforestation programmes are going on by governmental organizations, NGOs and local people.
- Improvements are needed in both GCMs and the scenario development techniques. Climate change scenarios and models should be selected so that the results will be directly comparable with historical observations.
- More accurate forecasting methodology is required to forecast the increases in GHGs in the atmosphere and changes in land use pattern to make sound decision to mitigate or adapt to new conditions.
- Hydrological models should incorporate better physical based understanding of processes and their interaction. Parameter measurement and estimation techniques must be developed further for using over a range of spatial and temporal scales.
- Maintenance and installation of observation network for the Himalayan region to monitor and evaluate the impacts of climate change. International research organization and funding agencies should focus on areas with scarce data.

- Budget planning should permit sufficient flexibility to accommodate departments to deal with extreme climatic events.
- Better communication and interaction between planners, researchers, and policy makers are needed. Better cooperation and support among neighbouring countries are needed to cope with climate-induced disasters.
- Involvement of community is important at all decision-making levels. It helps in generating more awareness of climate change issues and develops a better understanding of the impacts and potential adaptation measures available to decision-makers and local level community.
- Monitoring and evaluation programs should be implemented as an ongoing activity to determine if supplemental adaptation measures need to be considered.

Recommendations

Adaptation to climate change has the potential to substantially reduce many of the adverse impacts of climate change and enhance beneficial impacts. The key features of climate change vulnerability and adaptation are those related to variability and extremes, not specifically changed average conditions. Developing countries like India with limited economic resources, poor infrastructure; insufficient levels of technology, information and skills; traditional and non-responsive bureaucratic institutions coupled with inequitable empowerment and access to resources has inadequate capacity to adapt and is highly vulnerable. Enhancement of adaptive capacity is a necessary condition for reducing vulnerability to climate induced changes in availability of water resources, frequency and intensity of extreme events like floods, droughts, heat and cold waves, fragile coastal ecosystems and the associated impacts on agriculture and other livelihood options (Sharma and McCornick, 2006). For a comprehensive, integrated and futuristic policy framework on adaptation to climate change in water resources the following recommendations need to be seriously considered.

1. **Improving Institutional Capacity**

There is a pressing need for improvement and strengthening of existing institutional arrangements and systems to make the initial response to a disaster more effective and professional. Some of the areas where improvement is urgently needed are:

i. Integrated planning for extreme climatic events/ disasters at all levels from district to state and central government. This also needs to include the relevant communities and civil society organizations.
ii. Provision of adequate financial support to the on-going/ new centrally sponsored development schemes, which enhance the adaptation and reduce disaster vulnerability of the communities. Even the High Powered Committee of the national Planning Commission has advised that 10 per cent of the plan funds at the national, state and district levels be used for schemes which specifically address prevention, reduction, preparedness and mitigation of extreme events (no regret measures).

iii. Build a comprehensive, robust and accessible database of the land use, demography and infrastructure along with current information on climate, weather, water resource structures etc. for accurate planning, warning and assessment of impacts. Much of the necessary data already exists, but either because of security concerns or institutional constraints is not readily available.

iv. Establish a National Network of all knowledge- based institutions which research and share community of best practices with extreme event managers, decision makers, communities and all other stakeholders.

v. Insurance can be powerful tool for reducing vulnerability to climate change by transferring or sharing risk. Weather-indexed insurance can help farmers protect their overall income rather than yield of a specific crop and reduce overall vulnerability to climate variability and change.

2. Development and Management of Water Resources

Water managers have experience adapting to change. Adaptations can involve management on the supply side (e.g., altering infrastructure or institutional arrangements) and on the demand side (changing demand or risk reduction). The following no-regret policies shall generate net social benefits regardless of climate change.

i. Enhance water storage capacity: Per capita dam storage capacity in India is one of the lowest in the world (200 m^3/capita as compared to 5000 m^3 in the USA, 1000 m^3 in China, and around 900 m^3 in South Africa) and needs to be substantially enhanced to offset the seasonal and long term resource availability fluctuations and make efficient use of the available resources.

ii. Capture the glacial and snowmelts: It has been predicted that global warming in the tropics shall cause enhanced deglaciation and snowmelts during the next 7 to 8 decades in the northern Himalayas. This calls for effective capture of these additional resources to tide over the subsequent reduced supplies and mitigate the impact of flash floods.

iii. Inter-basin transfers of some form are most likely inevitable. The Government of India has already developed a National Integrated Water Development Plan and National River Linking Project. This calls for the transfer of water from relatively water rich eastern (and possibly northern) Himalaya river to the deficit southern basins. At least portions of this project are likely to be implemented, but require a strategic analysis of the available options and concerns raised by environment and social groups.

iv. Mitigation measures on individual structures can be achieved through improved design standards and performance specifications. In order to save larger outlays on rehabilitation and reconstruction subsequently, a mechanism would need to be worked out for allowing components that specifically help projects developed in disaster prone areas withstand the impact of the large variations/natural disasters (land slides, flash floods, flow blockages etc.).

v. Enhance water productivity at all levels through field, farm, and command area and basin level improvements. Multiple uses of water, ensuring hydrological sustainability of intensive cropping systems, reducing non-beneficial evaporation losses, breeding drought/ flood tolerant and water efficient cultivars and community participation in resource management shall help in demand management of the resources.

3. Adaptation to Floods

The traditional flood control and flood management methods already in place in the country need to be streamlined, modernized and made effective to take care of more frequent, intense and potentially unprecedented floods inundating vast land areas. More specifically, the following steps shall be useful:

i. In the vast low lying areas in the east people have to live with floods and learn better techniques to minimize losses with more reliance on non-structural measures. Integrated farming systems with suitable blend of aquaculture and agriculture can provide better livelihood means for the vulnerable communities, and. If appropriately design, can be more resilient to extreme events.

ii. Existing flood forecasting methodology may be refined by using computer based comprehensive catchments modeling using real time and remotely sensed data and GIS. The present lead-time of 12 hours to 72 hours needs to be enhanced for better preparedness and evacuation/ relief operations.

iii. The water level forecast (which makes little sense to the user agencies) need to be converted into potential area inundation forecast so that relief and rehabilitation response is better targeted.

iv. Updating and digitization of flood plain zoning maps and better enforcement of flood plain zoning regulations shall considerably mitigate the flood impacts.

v. Encourage community participation in flood management, as they will have better knowledge of local needs and potential and building quick resilience. This shall require setting up of a community oriented and empowered institutional framework backed by strong capacity building measures.

4. Prevention and Management of Droughts

Drought management in India, despite being efficient and proactive, is still an ad-hoc and empirical famine intervention for providing instant relief to prevent starvation

(Samra, 2004). The concept of an institutionalized process of management consisting of vulnerability mapping, community involvement, prevention, mitigation, quick responses, a comprehensive relief mechanism, use of modern tools and procedures of monitoring, impact documentation and capacity building is not yet fully in place in India. The following no-regret measures shall be helpful in better management and mitigation of droughts:

i. The existing traditional, time consuming and bureaucratic system of drought declaration and management may be replaced with a comprehensive, objective but decentralized or community empowered institutionalized system of drought declaration and management.
ii. Detailed vulnerability maps of droughts based on long-term trends and real time data are essential for developing strategic management plans.
iii. Prevention, mitigation, preparedness, institutional infrastructures, capacity building and logistic of relief material for a quick response should be planned and located according to vulnerability level of the region.
iv. Decision support systems for estimating losses of crops, orchards, trees, grasslands, livestock, surface and groundwater resources may be calibrated for different vulnerable regions and livelihood opportunities.
v. Crop- centered management policy should shift in favor of robust and integrated livestock, trees, agro-forestry and grassland based livelihood opportunities along with promotion of off-farm income generation skills.
vi. Water harvesting at local, community and regional level should be considered as a long-term strategic intervention for mediating the drought impacts.

CONCLUSIONS

Global climatic changes will have major effects on precipitation, water availability, glacier/ice melt, and sea level rise. Climate-induced changes in hydrological conditions will affect the magnitude, frequency, and damage costs of future extreme events. There is evidence that flooding is likely to become a larger problem in South Asian countries. The most significant uncertainties are the changes in precipitation and runoff projected by large-scale general circulation models. Uncertainties exist in translating large-scale climatic changes into specific regional impacts because of problems with models and data, and because many of the human impacts will depend on economic, technological, and institutional factors that help define our water system. Climate change will affect the demand as well as the supply of water and may influence a wide range of water-system components, including reservoir operations, water quality, hydroelectric generation, and navigation. Impacts of climate change will depend on the baseline condition of the water resource system and the ability of water resources managers to respond not only to climate change but also to population growth and changes in demands, technology, and economic, social, and legislative conditions.

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