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Climate change and water availability in Indian agriculture: Impacts and adaptation

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ABSTRACT

Climate is a very decisive factor in water resource availability of a region. Warming of the climate system in recent decades is evident from increase in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. The hydrological cycle is intimately linked with changes in atmospheric temperature and radiation balance. A warmer climate may lead to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, may affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves etc. and may increase the frequency of droughts and floods. Agricultural demand, particularly for irrigation water is considered more sensitive to climate change. A change in field-level climate may alter the need and timing of irrigation. Increased dryness may lead to increased demand, but demand may be reduced if soil moisture content rises at critical times of the year. It is projected that most irrigated areas in India would require more water around 2025 and global net irrigation requirements would increase relative to the situation without climate change by 3.5–5% by 2025, and 6–8% by 2075. The effect of climate change on water resources may be mitigated through better water harvesting through the creation of micro-storage facilities in watersheds. These would not only provide supplemental irrigation but also recharge the groundwater aquifers.

Key words: Climate change, Integrated water resource management, Water, Water use efficiency

India with 2.4% of the world's total area has 16% of the world's population; but has only 4% of the total available fresh water. Its geographical area of 328.726 Mha is covered by a large number of small and big rivers. Over 70% of India's population of more than one billion is rural and agriculture oriented, for whom these rivers are the source of their livelihood and prosperity. Rainfall in India is mainly dependent on the south-west monsoon between June to September, and the north-east monsoon between October and November. The annual precipitation including snowfall, which is the main source of water in the country, is estimated to be of the order of 4000 km^3. The variations in temperature are also marked over the Indian sub-continent. During the winter season from November to February, the temperature decreases from south to north due to the effect of continental winds over most of the country. Central areas of the country display the highest evapo-transpiration rates during April and May which closely follow the climatic seasons, and reach their peak in these summer months. After the onset of monsoon, potential evapo-transpiration decreases generally all over the country.

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There are 12 major river basins in India with individual catchment area of more than 10 Mha and a cumulative catchment area of 252.8 Mha (Table 1). Average annual potential in rivers is about 1571 billion m^3 (BCM), i e 85% of the total natural run-off. Of the major rivers, the Ganga-Brahmaputra-Meghna system is the largest, with a catchment area of about 110 Mha which is more than 43% of the cumulative catchment area of all the major river basins in the country. This river system is the major contributor (about 60%) to the surface water resource potential of the country. The other major rivers with a catchment area of more than 10 Mha each are the Indus (32.1 Mha); Godavari (31.3 Mha); Krishna (25.9 Mha); and Mahanadi (14.2 Mha). Another 48 rivers are classified as medium rivers (CWC 2002), whose total catchment area is 24.9 Mha. With a 1.9 Mha catchment area, Subernarekha is the largest river amongst the medium rivers in the country. The total annual discharge in the rivers that flows in various parts of the country amounts to 1869 km^3. Many of these rivers are perennial, though few are seasonal. This is because precipitation over a large part of India is strongly concentrated in the summer monsoon season during June to September/October and the tropical storm season from May to October (Kale 2003). Rivers do not remain at a high stage throughout the monsoon season but only a spell of heavy rains lasting for a period of several hours to few days

Table 1 Major river basins of India

River	Origin	Catchment area (km^2)	Average annual potential in river (Bm^3/yr)
Indus	Mansarovar (Tibet)	321289 +	73.31
Ganga	Gangotri (Uttar Kashi)	861452 +	525.02
Brahmaputra Barak and others	Kailash Range (Tibet)	194413 +	585.60
Sabarmati	Aravalli Hills (Rajasthan)	21674	3.81
Mahi	Dhar (Madhya Pradesh; MP)	34842	11.02
Narmada	Amarkantak (MP)	98796	45.64
Tapi	Betul (MP)	65145	14.88
Brahmani	Ranchi (Bihar)	39033	28.48
Mahanadi	Nazri Town (MP)	141589	66.88
Godavari	Nasik (Maharashtra)	312812	110.54
Krishna	Mahabaleshwar (Maharashtra)	258948	78.12
Pennar	Kolar (Karnataka)	55213	6.32
Cauvery	Coorg (Karnataka)	81155	21.36
Total		2528084	1570.98
Other river basins of the country		248505	298.02
Total		2776589	1869.00

Source: CWC (2002)

may generate large run-off in the catchments (Kale 1998). The water resource potential of the country, occurring as natural run-off in the rivers, is about 1869 km^3 (CWC 2002, Table 2). While India is considered rich in terms of annual rainfall and total water resources, its uneven geographical distribution causes severe regional and temporal shortages.

Impact of climate change on surface water resources

The effect of climate change on surface water resources is based on temperature, rainfall and water yield in these river basins. Various studies are being carried out to see the effect of climate change on water yield in these river basins. The studies used the grid data of Indian Meteorological Department (IMD) or HadRM2 daily weather data to predict the water balance components. Because of lack of rain gauge stations and long term historical data of point rainfall in the catchment areas, the trends for temperature are more realistic than water yield. The studies of basin-wise impacts of climate change on water resources availability indicate that climate change is likely to affect the hydrological cycle, which will result in (i) more rainfall in lesser time; (ii) decrease in number of rainy days; (iii) overall increase in precipitation; (iv) increased glacial-melt-runoff initially and then afterwards decrease; (v) increase in runoff but less ground water recharge; (vi) increase in flood events particularly of flash floods; (vii) increase in drought like situations; (viii) increase in landslide events in hilly areas, and some other related issues etc.

Table 2 Water resources of India

Parameters	Amount (Bm^3)
Annual precipitation	4000
Available water resources	1869
Utilizable water	1122
Surface water (storage and diversion)	690
Ground water (replenishible)	432
Present utilization (surface water 63%, ground water 37%)	605
Water use for irrigation	501
Water use for domestic purposes	30
Water use in industry, energy and other sectors	74

Source: Mall *et al.* (2006)

Another source of water is groundwater resources which have static and dynamic components. The static fresh groundwater reserves (aquifer zones below the zone of groundwater table fluctuation) of the country have been estimated as 10812 BCM. The dynamic component which is replenished annually has been assessed as 432 BCM. According to the National Water Policy (2002), development of groundwater resources is to be limited to utilization of the dynamic component of groundwater. It is equally important to consider the potential impacts of climate change on groundwater systems. As part of the hydrologic cycle, it can be anticipated that groundwater systems would be affected by changes in recharge, which encompasses changes in precipitation and evapo-transpiration, potentially by changes in the nature of the interactions between groundwater and surface water systems, and changes in use related to irrigation.

Water demand

At present, available statistics on water demand shows that agriculture sector is the largest consumer of water in India. About 83% of available water is used for agriculture alone. Based on 1991 Census, per capita availability of water works out to 1967 m^3. Due to various constraints of topography, and uneven distribution of resources over space and time, it has been estimated that only about 1122 km^3 of its total potential can be put to beneficial use, of which 690 km^3 is from surface water resources. Further, about 40% of utilizable surface water resources are presently in the Ganga-Brahmaputra-Meghna system. In majority of river basins, present utilization is significantly high and is in the range of 50-95% of utilizable surface resources. However, in rivers such as the Narmada and Mahanadi, percentage utilization is quite low being 23% and 34%, respectively. On the other hand, ground water is another major component of the total available water resources. In the coming years ground water utilization is likely to increase manifold for expansion of irrigated agriculture and to achieve national targets of food production. Although ground water is an annually replenishable resource, its availability is nonuniform in space and time. Based on the norms given by the Ground Water Overexploitation Committee, the state governments and the Central Ground Water Board computed the gross ground water recharge as 431.42 km^3, and the net recharge (70% of the gross) as 301.99 km^3. The issue of demand management has been given due importance in order to achieve higher levels of water use efficiencies.

The quantity of water required for agriculture has increased progressively through the years as more and more areas were brought under irrigation. Since 1947, irrigated area in India rose from 22.60 to 80.76 Mha up to June 1997. Contribution of surface water and groundwater resources for irrigation has played a significant role in India for attaining self-sufficiency in food production during the past three decades, but it is likely to become more critical in future in the context of national food security and climate change. According to available estimates, due to judicious utilization, the demand on water in this sector is projected to decrease to about 68% by the year 2050, though agriculture will still remain the largest consumer. In order to meet this demand, augmentation of the existing water resources by development of additional sources of water or conservation of the existing resources through impounding more water in the existing water bodies and their conjunctive use will be needed. In 1999, National Commission for Integrated Water Resources Development estimated the water requirements for the years 2010, 2025 and 2050 at the national level (Table 3). Fig 1 shows water requirements for different sectors in India.

Relationship of climate change and water

Water is involved in all components of climate system, i e atmosphere, hydrosphere, cryosphere, land surface and biosphere. Climate change affects hydrological cycle through a number of mechanisms such as changing precipitation patterns, intensity and extremes; widespread melting of snow and ice; increasing atmospheric water vapour; increasing evaporation; and changes in soil moisture

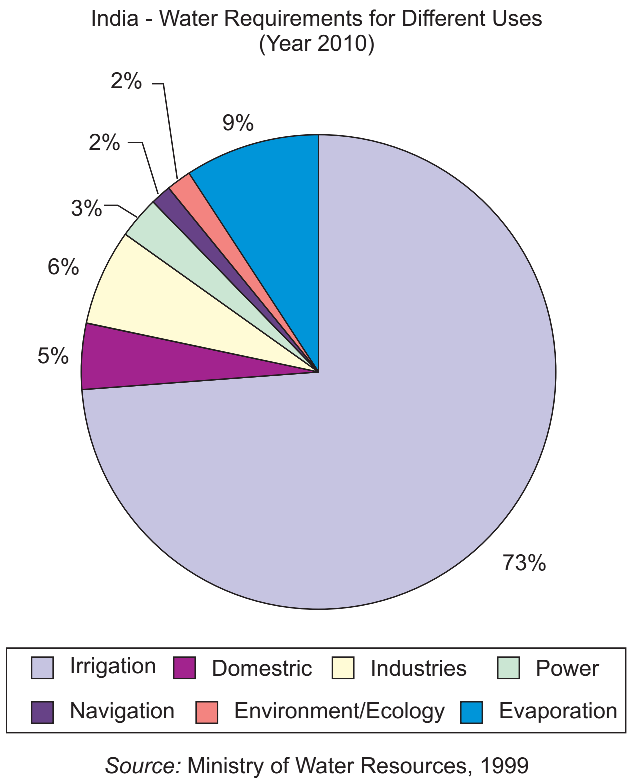

Fig 1 Water requirements for different uses in India (MOWR 1999).

Table 3 Utilizable water, requirement and return flow over the years

Particulars	1997-98	2010		2025		2050	
		Low demand	High demand	Low demand	High demand	Low demand	High demand
Utilizable water				km³			
Surface	690	690	690	690	690	690	690
Ground	396	396	396	396	396	396	396
Canal irrigation	90	90	90	90	90	90	90
Total	996	996	996	996	996	996	996
Total water requirement							
Surface	399	447	458	497	545	641	752
Ground	230	247	252	287	298	332	428
Total return flow	629	694	710	784	843	973	1180
Surface	43	52	52	70	74	91	104
Ground	143	144	148	127	141	122	155
Total	186	196	200	197	215	213	259
Residual utilizable water							
Surface	334	295	284	263	219	140	42
Ground	219	219	202	146	149	96	33
Total	553	553	486	409	368	236	75

Source: NCIWRD (1999)

and runoff. The hydrological cycle is intimately linked with changes in atmospheric temperature and radiation balance. Warming of the climate system in recent decades is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. Net anthropogenic radiative forcing of climate is estimated to be positive (warming effect), with a best estimate of 1.6 W/m^2 for 2005 (relative to 1750 pre-industrial values). The best-estimate linear trend in global surface temperature from 1906 to 2005 is a warming of 0.74°C (likely range 0.56 to 0.92°C), with a more rapid warming trend over the past 50 years. For widespread regions, cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent over the past 50 years.

The climate response to forcing agents is also complex. For example, one effect of absorbing aerosols (e.g. black carbon) is to intercept heat in the aerosol layer which would otherwise reach the surface, driving evaporation and subsequent latent heat release above the surface. Hence, absorbing aerosols may locally reduce evaporation and precipitation. Rising global temperatures will lead to an intensification of the hydrological cycle, resulting in dryer dry seasons and wetter rainy seasons, and subsequently heightened risks of more extreme and frequent floods and drought. Changing climate will also have significant impacts on the availability of water, as well as quality and quantity of available and accessible water. Melting glaciers will increase flood risk during the rainy season, and strongly reduce dry-season water supplies to one-sixth of the world's population. Melting ice and thermal expansion of oceans are the key factors driving sea level rise. In addition to exposing coastlines, where the majority of the human population lives, to greater erosion and flooding pressures, rising sea levels will also lead to salt water contamination of groundwater supplies, threatening the quality and quantity of freshwater access to large percentages of the population. Any adverse impact on water availability due to recession of glaciers, decrease in rainfall and increased flooding in certain pockets would threaten food security, cause die back of natural ecosystems including species that sustain the livelihoods of rural households, and adversely impact the coastal system due to sea level rise and increased frequency of extreme events.

Temperature drives the hydrological cycle, influencing hydrological processes in a direct or indirect way. A warmer climate may lead to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, may affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves etc. and may increase the frequency of droughts and floods. An increase in mean temperatures would increase the energy flux for evapo-transpiration. The changes in seasonal temperatures could change the crop seasons. The future climatic change, though, will have its impact globally but likely to be felt severely in developing countries with agrarian economies, such as India. Surging population, increasing industrialization and associated demands for freshwater, food and energy would be areas of concern in the changing climate scenarios. Increase in extreme climatic events will be of great consequence owing to the high vulnerability of the region to these changes. Table 4 shows decreasing per capita water availability in India.

Due to change in weather pattern there will be acute scarcity of drinking water in some parts of the country especially North and North West parts of India. The snow and ice mass in the Himalayan range is the third largest in world, after the Greenland and the Antarctica ice sheets. There has been a noticeable increase in snow melt and if this continues, it will affect the water supply of much of Asia.

Table 5 Impact of climate change on water resources during the next century over India

Region/location	Impact
Indian subcontinent	Increase in monsoonal and annual run-off in the central plains
	No substantial change in winter run-off
	Increase in evaporation and soil wetness during monsoon and on an annual basis
Orissa and West Bengal	One metre sea-level rise would inundate 1700 km^2 of prime agricultural land
Indian coastline	One metre sea-level rise on the Indian coastline is likely to affect a total area of 5763 km^2 and put 7.1 million people at risk
All-India	Increases in potential evaporation across India
Central India	Basin located in a comparatively drier region is more sensitive to climatic changes
Kosi Basin	Decrease in discharge on the Kosi River and decrease in run-off by 2–8%
Southern and Central India	Soil moisture increases marginally by 15–20% during monsoon months
Chenab river	Increase in discharge in the Chenab river
River basins of India	General reduction in the quantity of the available run-off, increase in Mahanadi and Brahmini basins
Mahanadi river basin	Increasing intensities of flood
Damodar Basin	Decreased river flow
Rajasthan	Increase in evapo-transpiration
Kasnabati river basin	Increase in transmission losses, soil water content, potential evapo-transpiration, evapo-transpiration and lateral flow to reach
Lower Brahmaputra	Low flows less frequent and increased peak flow
Sutluj Basin	Little change in total stream flow but substantial change in the distribution of stream flow
Damodar and Rupnarayan river	West Bengal would have more virtual water than Jharkhand

Source: Mall *et al.* (2006)

Projected demand and supply of water with climate change

The hydrological cycle, a fundamental component of climate, is likely to be altered in important ways due to climate change. Using the Soil and Water Assessment Tool (SWAT) water balance model for hydrologic modeling of different river basins in the country, in combination with the outputs of HadRM2 regional climate model, preliminary assessments have revealed that under the IS92a scenario, the severity of droughts and intensity of floods in various parts of India is likely to increase. Further, there is a general reduction in the quantity of available runoff under the IS92a scenario. River basins of Sabarmati and Luni, which occupy about one quarter of the area of Gujarat and 60 percent of the area of Rajasthan, are likely to experience acute water scarce conditions. River basins of Mahi, Pennar, Sabarmati and Tapi are likely to experience constant water scarcity and shortage. Majumdar (2008) overviewed the current water resources scenario and recent work carried out in India to assess the climate change impact on hydrology and water resources. The study suggested various research activities to be carried to assess the impact of global climate change on surface water availability and demands, as well as the intensity and frequency of hydrologic extremes of floods and droughts.

Variations in climate, land-use, urbanization and water consumption also have profound effects on river runoff. The effect of climate variability on Krishna river runoff was not as profound as compared to the water consumption (Bouwer *et al.* 2006). In similar way, water availability in the Ganga basin is also affected by urbanization (Mishra 2011). The future trends in low and high flows of lower Brahmaputra indicate that extreme low flow conditions are likely to occur while very strong increase in peak flows is expected which may, in combination with projected sea level change, could have devastating effects for Bangladesh (Gain *et al.* 2011). Asokan and Datta (2008) showed that the highest increase in peak runoff (38%) in the Mahanadi River outlet will occur during September, for the period 2075–2100 and the maximum decrease in average runoff (32.5%) will be in April, for the period 2050–2075. The outcome of the study indicated that the Mahanadi River Basin is expected to experience progressively increasing intensities of flood in September and drought in April over the considered years. Singh and Bengtsson (2004) and Singh *et al.* (2006) indicated that runoff in the glacierzed Himalayan region which contributes about 50% of Indian water resources, increased linearly with increase in temperature and rainfall. For a temperature rise of 2 °C, the increase in summer stream flow is expected to be about 28%. Changes in rainfall by ±10% resulted in corresponding changes in stream flow by ±3.5%. The changes in runoff are more sensitive to changes in temperature, compared with rainfall, which is likely due to the major contribution of melt water in runoff. The transmission losses, soil water content, potential evapo-transpiration, evapo-transpiration and lateral flow to reach in the Kangsabati river catchment located in Bankura district of West Bengal, displayed an increasing trend over the time period of years 2041–2050 under the climate change scenarios (Dhar and Mazumdar 2009). Jain *et al.* (2010) used plausible climate scenarios including three temperature scenarios (T +1°C, T + 2°C, T + 3°C). The effect of these changes has been studied on the stream flow which has contribution from snowmelt, rainfall and base flow in the Satluj basin. It was observed that with increase in temperature there is not much change in total stream flow, but distribution of stream flow have changed. More snowmelt runoff occurred earlier due to increased snow melting, however, reduced in the monsoon months. The impact of climate change in Sutluj river basin was found to be more prominent on seasonal rather than annual water availability. Reduction of water availability during the summer period, which contributes about 60% to the annual flow, may have severe implications on the water resources of the region, because demand of water for irrigation, hydropower and other usage is at its peak at this time (Singh and Bengtsson 2004).

In India, irrigation in majority of states has been transformed from a centrally managed surface irrigation regime to atomistically managed water scavenging irrigation regime involving tens of millions of pump owners who divert surface and groundwater at will (Shah 2009). In all these states, irrigation is dependent on groundwater through public or private tube wells. Ground water inventory is presently 0.34 million km^3. Although efforts are being made to promote improved water management practices such as water conservation, artificial recharge and watershed management, and integrated water development, projected water demand of over 980 billion cubic meters in 2050 will require intensive development of ground water resources, exploiting both dynamic and in-storage potential. Dryland farming (approx. 60% of cultivated area) contributes around 40% of total food production. Proper farm level management strategies like in-situ water conservation, on-farm generation of organic manure, alternate land use, cropping system and diversification into agri-horti-livestock can be practiced in dryland areas. Climate change will affect the groundwater availability in terms of both quantity and quality (in particular coastal aquifers) and present new uncertainties. It is obvious that the projected climate change resulting in warming, sea level rise and melting of glaciers will adversely affect the water balance in different parts of India and quality of ground water along the coastal plains. The snow melt runoff gets declining; it may seriously affect the recharge to groundwater causing shortage in water availability in Punjab, Haryana, Uttar Pradesh and Rajasthan. Climate change is likely to affect ground water due to changes in precipitation and evapo-transpiration. Increased rainfall intensity may lead to higher runoff and possibly reduced recharge (Ministry of Environment and Forest, 2004). This recharge may create more floods in Indo-Gangetic plains and but changed pattern of rainfall would affect the coastal aquifers. Depending upon the spatial as well as temporal distribution of monsoon season rainfall with increasing trend (+10% to +12% of the normal) in parts of northern Andhra Pradesh, and north-western India (Rajasthan) may possibly enhance the quantum of ground water recharge. These areas have very high percentages of over exploited/critical blocks; this may be advantageous from recharge and irrigation availability as well as energy consumption point of view. However, for eastern Madhya Pradesh and some parts of Gujarat and Kerala increase in temperature and decline in rainfall (-6% to -8% of the normal) may reduce net recharge and affect groundwater resource availability. From a climate change point of view, India's groundwater hotspots are western and peninsular India (Shah 2009).

Rising sea levels may lead to increased saline intrusion into coastal and island aquifers, while increased frequency and severity of floods may affect groundwater quality in alluvial aquifers. Unnikrishnan and Shankar (2007) concluded a sea level rise between 1.06 and 1.75 mm per year, consistent with the 1–2 mm per year global sea level rise estimates of IPCC. Rising sea levels will threaten coastal aquifers. Many of India's coastal aquifers are already experiencing salinity ingress. This problem is particularly acute in Saurashtra coast in Gujarat and Minjur aquifer in Tamil Nadu (Shah 2009). Thus, coastal aquifers are likely to face groundwater quality problems due to sea level rise. Other studies by TERI (1996) indicated that most vulnerable areas along the Indian coastline due to sea level rise are the Kutch region of Gujarat, Mumbai and South Kerala. Deltas of rivers Ganges (West Bengal), Cauvery (Tamil Nadu), Krishna and Godavari (Andhra Pradesh), Mahanadi (Odisha) and also the islands of Lakshadweep Archipelago would be totally lost. In the coastal regions of Tamil Nadu, salinity of groundwater due to the intrusion of seawater into the subsurface aquifer is a major problem (Subramanian 2000). Due to excess withdrawal of groundwater, the water table has fallen too far below thereby allowing seawater to percolate. Similarly, in Gujarat due to uncontrolled withdrawal of groundwater, ground water is becoming highly saline apart from the fact that depth of the water table reaching at places beyond 200 meters (Subramanian 2000). These states are largely dependent on groundwater resource for irrigation purpose leading to crisis due to poor groundwater quantity and quality. Impact of climate change on water resources during the next century over India has been studied by several researchers (Table 5).

Man-made climate changes, i e changes in cropping pattern and land-use pattern, over-exploitation of water storage and changes in irrigation and drainage in the Gangetic basin show a reduction in the Ganges discharge by 60% over 25 years. This has led to about 50% drop in water availability in surface water resources, drop in groundwater table and generation of new surface features having different thermal properties (Adel 2002). Agricultural demand, particularly for irrigation water, which is a major share of total water demand of the country, is considered more sensitive to climate change. A change in field-level climate may alter the need, number and timing of irrigation. Increased dryness may lead to increased demand, but demand could be reduced if soil moisture content rises at critical times of the year. It is projected (Doll and Siebert 2001) that most irrigated areas in India would require more water around 2025 and global net irrigation requirements would increase relative to the situation without climate change by 3.5–5% by 2025, and 6–8% by 2075. In India, about 52% of irrigation consumption across the country is extracted from groundwater; therefore, it can be an alarming situation with decline in groundwater and increase in irrigation requirements due to climate change. Majumdar *et al.* (2010) studied the impact of climatic uncertainties on availability of virtual water using neurogenetic models on two major river networks of East India, Damodar and Rupnarayan. The study indicated that West Bengal would have more virtual water than Jharkhand state. The magnitude of virtual water availability showed increasing trend in both the scenario of climate change where the change is more pronounced in B2 than in A2 scenarios of PRECIS model. Gosain *et al.* (2006) studied per cent change in mean annual water balance components for control and GHG climate scenarios for different river basins of India (Fig 2).

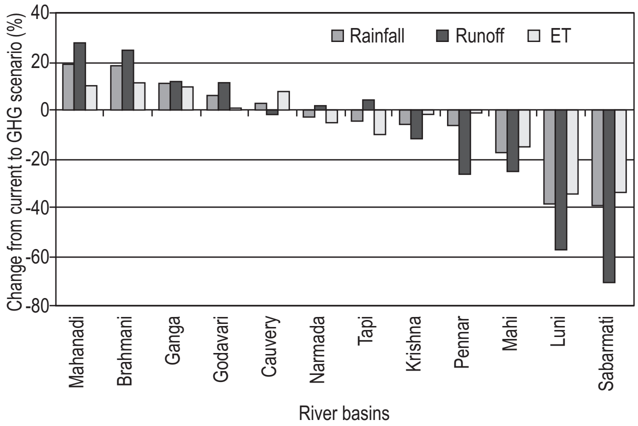

Fig 2 Percent change in mean annual water balance components for control and GHG climate scenarios (Gosain *et al.* 2006).

Strategies to mitigate water stress due to climate change

Increasing availability of usable water

This may be done by reducing the wastage of water, increasing water harvesting capacity of the system and increasing recharge. The effect of reduction in rainfall due to climate change could be mitigated through better water harvesting through the creation of micro-storage facilities in watersheds. These would not only provide supplemental irrigation but also recharge groundwater aquifers particularly in Punjab, Gujarat and Rajasthan. Lining of water conveyance systems in selected reaches where large seepages leading to waterlogging would be occurring, is necessary. Existing large reservoir operating policies need to be redeveloped to take into the effect of climate change. The demand patterns are also likely to be affected because of climate change. Thus, in the operation policies for conservation purposes, due considerations may have to be given to the changed demand patterns. The policies are also developed for real time operation of reservoirs for mitigating the floods. Conjunctive use of surface water and groundwater needs to be planned for irrigation under changed climatic scenarios for sustainable developments in the basins. There is a need to create large carry over storages but also storages in the vadose zone of aquifers. Inter-basin or long distance transfer of water and water trading may increase the water availability in the deficit river basins.

Since fresh water supplies are limited and has competing uses, agriculture has to start vigorous evaluation of using industrial and sewage wastewater. Such effluents, once properly treated, can also be a source of nutrients for crops. Since water serves multiple uses and users, effective inter-departmental coordination in the government is needed to develop the location specific framework of sustainable water management and optimum recycling of water.

Improving the efficiencies for water use

The efficiencies of individual on farm water systems need to be improved to ensure that water withdrawn from the natural system, after considerable use of resources is used in an efficient way. Proper leveling of farms could improve the water application efficiencies by over 20%. Laser leveling may be employed on large scale to level the irrigation layouts to improve water use. Proper designing of farm layouts would also improve the water application and use efficiencies. A relook on the water pricing and realistic values could promote efficient use of natural resources. Automation, computer controlled decision support systems, on demand irrigation through creation of level pools in canals, using real time soil moisture data to decide irrigation doses etc. are important means of improving efficiency. Use of modern irrigation methods such as micro-irrigation should be promoted to enhance water use efficiency. Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields to when planted under normal conventional tillage over a diverse set of soil conditions. This reduces costs of production, allows earlier planting and thus higher yield, results in less weed growth, reduces the use of natural resources such as fuel and steel for tractor parts, and shows improvements in efficiency of water and fertilizers. Availability of assured prices and infrastructure could create a situation for better utilization of groundwater. Policies should to be evolved that would encourage farmers to enrich organic matter in the soil and thus improve soil health such as financial compensation/incentive for green manuring.

Groundwater measures

Based on climate change viewpoint, India's groundwater hotspots are concentrated in arid and semi-arid areas of western and peninsular India, especially in the seven states of Punjab, Rajasthan, Maharashtra, Karnataka, Gujarat, Andhra Pradesh, and Tamil Nadu (Shah 2009). These states need an aggressive, nationwide Managed Aquifer Recharge programme which can enhance natural recharge rates to bring them closer to groundwater utilization rates on an annual basis. Another adaptation measure could be rationing the power supply system as adopted by the State of Gujarat in Jyotigram scheme could result in efficient use of groundwater. The use of efficient water utilization methods such as micro-irrigation coupled with groundwater use may lead to reduction in depletion of groundwater. In the states of Rajasthan, Maharashtra, Tamil Nadu and Karnataka, use of micro-irrigation technologies have reduced water consumption and increased crop yields by many folds. Another measure may be switching to aquifer storage rather than surface storage which may result in reduced evaporation loss. Conjunctive management of surface and groundwater in Punjab offers large opportunities for improving water productivity as well as saving energy. Conjunctive management can aim at minimizing average pumping depth of groundwater by spreading water over the command area (Shah 2009).

Water transfers between basins

The potential for water transfers between river basins is an option strongly considered for alleviating reduced water availability in some of the southern states. Major objective here is to transfer water from water rich basins of rivers such as Ganga, Brahmaputra, and Godavari to water scarce central, western and southern regions.

Altered agronomy of crops

Small changes in climatic parameters can often be managed reasonably well by altering dates of planting, spacing and input management. Alternate crops or cultivars more adapted to changed environment can further ease the pressure. For example, in case of wheat, early planting or use of longer duration cultivars may offset most of the loss associated with increased temperatures in South Asia. Many wheat varieties which consume lesser amount of water with least reduction in production could be introduced. Introduction of new rice growing technologies such as System of Rice Intensification (SRI) and Aerobic Rice Cultivation saves substantial amount of water which may be introduced in the rice growing areas. Available germplasm of various crops needs to be evaluated for heat and drought tolerance. Some of the management practices at farm level to mitigate water stress due to climate change are given below:

On-farm irrigation hydraulics:
- Laser land leveling, methods, design

Micro-irrigation systems:
- Hardware components
- Software components: Soil, Crop, ET

Cropping pattern/diversification:
- Rice to non-rice
- Adopting cropping pattern suited to the agro climatic-zones
- Reducing water demand especially in water intensive industries and household

- Change in land use
- Biotechnology: may help in increasing crop yields while reducing water requirement and developing crops that are less dependent on water
- Spread of drought-resistant crops

Improvement in groundwater use:

- Recharge, water harvesting, adjusting the pumping rate, multiple well point, reuse of drainage water

Development and Management Options:

- Evaluatory measures: Assessment and monitoring

Corrective measures:

- Artificial recharge, water harvesting including roof top rain water harvesting, sub-surface drainage, conjunctive use, water shed development, increasing the storage capacities, inter linking of rivers,
- Construction of dams, construction of levies and dikes, artificial restoration of the hydrological system

Protective measures:

- Effluent treatment and safe disposal of pollutants
- Flood plain zoning, flood forecasting systems, flood insurance and flood preparedness, technological management: medium (seasonal) to long-term (annual to decadal) forecasts

Regulatory and legislative measures:

- Formulation of water resource development and use policy
- Convergence of funds available to various programmes for water resources development.
- Ensuring gender equity and making women partners in decision making and implementing water management schemes especially at village/local level.
- Crop insurance
- Expanded use of economic incentives to encourage water conservation and heavy levies on water wastage/ over use

Integrated Water Resources Management (IWRM)

The IWRM provides a useful framework for planning well coordinated and targeted adaptation measures to climate change. It is a systematic process to the sustainable development and equitable allocation of water resources through a holistic approach to water management. Successful IWRM strategies include, among others: capturing societal views, reshaping planning processes, coordinating land and water resources management, recognizing water quantity and quality linkages, combined use of surface water and groundwater, protecting and restoring natural systems, addressing impediments to the flow of information, and including consideration of climate change. But there is also a risk in that IWRM, by being so ambitious, can encounter barriers both because it potentially challenges existing hierarchies and sectoral thinking, and because it may be too resource-intensive to apply in its entirety.

Development and management of water resources

The following no-regret policies shall generate net social benefits regardless of climate change.

- 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/capita in the USA, 1000 m^3/capita in China, and around 900 m^3/capita in South Africa) and needs to be substantially enhanced to offset the seasonal and long term resource availability fluctuations and make efficient use of available resources.
- Capture the glacial and snowmelts: It has been predicted that global warming in the tropics shall cause enhanced deglaciation and snowmelts during 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.\
- 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.
- 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.).
- 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.

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