
Climate Change and Water Security in Dry Areas

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Abstract

Water quality is deteriorating and its availability is decreasing with time. This chapter presents the implications of climate change for water in agriculture and environment in dry areas. Further adaptation strategies for sustainable use of water resources under changing climatic conditions is proposed.

This chapter analyzes the impacts of climate change on water availability and its quality. It considers the ongoing adaptation efforts and the problems faced in implementing these strategies. Certain guidelines and recommendations for addressing climate change in the water sector are also proposed.

This chapter elucidates the impacts of climate change on water quality and availability. Factors that govern these impacts are highlighted and certain adaptation guidelines are proposed.

Water is a nonrenewable resource directly affected by climate change. All stakeholders, including policy makers, water managers, and water users will benefit from this chapter.

Climate change has significant impact on water quality and availability. However, not many studies have been devoted to exploring the impacts of climate change and the possible measures to mitigate these impacts on water resources. Thus, the management of original and valuable work on the subject is presented.

Keywords

Climate change • Water security • Dry areas • Environment • Mitigation • Adaptation

The Climate System and the Hydrological Cycle

The cryosphere (snow, ice, and frozen ground) on land stores about 75 % of the world's freshwater. In the climate system, the ice cover and its changes are intricately linked to the surface energy budget, the water cycle, and sea level change. More than one-sixth of the world's population lives in glacier or snowmelt-fed river basins (Stern 2007). Satellite data show that there have been decreases of about 10 % in the extent of snow cover since the late 1960s (Rangwala and Miller 2012).

The water reservoir such as ice caps, glaciers, and permanent snow are among the most sensitive indicators of climate change (Seiz and Foppa 2007), advancing when climate cools (e.g., during the Little Ice Age) and retreating when climate warms. Glaciers grow and shrink, both contributing to natural variability and amplifying externally forced changes. There are 5.773×10^6 cubic miles of water in ice caps, glaciers, and permanent snow. According to the National Snow and Ice Data Center, if all glaciers melt today, the seas would raise ≈ 230 ft. Luckily, that is not going to happen all in one go, but sea levels will rise. Initially, based mainly on aerial photographs and maps, this compilation has resulted in a detailed inventory of more than 100,000 glaciers covering a total area of 2.4×10^5 km². In preliminary estimates, based on the records, the remaining ice cover was estimated to be $\approx 4.45 \times 10^5$ km². The World Glacier Monitoring Service collects data annually on glacier retreat and mass balance. Mass balance data indicate 17 consecutive years of negative glacier mass balance.

Retreating mountain glaciers cover 680 km² of the earth surface, that is, 4 % of the total surface area of land covered by ice on earth. Mountain glaciers make 1 % of land ice; however, 99 % of mountain glaciers have been retreating since the mid-nineteenth century. The changes in sea level, snow cover, ice extent, and rainfall are consistent with warming climate near the earth surface.

The appearance of ice on lake, river, and sea surfaces requires prolonged periods with air temperatures below 0 °C. High air temperatures and warmer winds will affect the duration of ice cover, the freezing and thawing times, and the thickness of ice cover. Climatic conditions not only influence the timing and duration of the ice cover but also the thickness of the ice cover and the nature of breakup (Beltaos and Prowse 2009).

Driven by solar energy, the climate system is complex and interactive, comprising of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things (Parry 2007). The climate system evolves over time under the influence of its own internal dynamics and due to changes in external factors that affect climate. External factors include natural phenomena (e.g., volcanic eruptions, solar variations, etc.) as well as anthropogenic activities that alter atmospheric composition and land cover and land-use change. Alterations in any of these factors can modify the balance between incoming short-wave sun radiation and outgoing long-wave radiation. The climate system responds both directly and indirectly to such changes.

The hydrological cycle designates a continuous movement of water through oceans, atmosphere, and land surface. Powered by solar radiation, the hydrological cycle begins with the evaporation of water from the surface of the ocean, transported around the globe, and returns to the surface as precipitation (rain, snow, sleet, hail, etc.). Once water reaches the ground, one of two processes may occur: (i) water evaporates or transpires back into the atmosphere or (ii) water penetrates the surface and becomes groundwater. Groundwater seeps into oceans, rivers, and streams. The balance of water that remains on the earth's surface is runoff, which empties into lakes, rivers, and streams and is carried back to the oceans, where the cycle begins again (Várallyay 2010). Any variability in climate affects the hydrological cycle on earth which directly affects the water resources.

Climatic Change and its Drivers

Factors that can shape climate are often called climate forcing. These include such processes as variations in solar radiation, deviations in earth orbit, mountain-building, as well as continental drift and changes in concentrations of greenhouse gases. These are a variety of climate change feedbacks that can either amplify or diminish the initial forcing. Some parts of the climate system, like oceans and ice caps, react slowly to climate forcing because of their large mass. Therefore, the climate system can take centuries or longer to fully respond to new external forcing.

Climate change is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. Climate change is caused by factors that include oceanic processes (such as oceanic circulation), biotic processes, variations in solar radiation received by the earth, plate tectonics and volcanic eruptions, and human-induced alterations of the biosphere equilibrium; these latter effects are currently causing global warming, and “climate change” is often used to describe human-specific impacts.

Globally, the 1990s was the warmest decade and 1998 the warmest year in the instrumental record since 1861. New analyses of proxy data for the Northern Hemisphere indicate that an increase in temperature in the twentieth century is likely to have been the largest of any century during the past 1,000 years. Because fewer data are available, less is known about annual averages prior to 1,000 years.

On an average between 1950 and 1993, nighttime daily minimum air temperatures over land increased by about 0.2 °C per decade. This is twice the rate of increase in daytime daily maximum air temperatures (0.1 °C per decade). This has lengthened the freeze-free season in many mid- and high-latitude regions. The increase in sea-surface temperature over this period was about half that of the mean land surface air temperature. Arctic sea ice has decreased since 1973, when satellite measurements began. Since the start of the satellite record in 1979, both satellite and weather balloon measurements show that the global average temperature of the lowest 8 km of the atmosphere has changed by $+0.10 \text{ °C} \pm 0.05$ per decade, but the global average surface temperature has increased by $+0.15 \pm 0.05$ °C per decade. The record shows a great deal of variability, for example, most of the warming occurred during the twentieth century, during two periods, 1910–1945 and 1976–2000.

The Earth may have warmed by an average of more than 1.7 °C over the past 150 years according to an analysis of the University of Wisconsin study of the freeze and thaw records for lakes and rivers in the Northern Hemisphere. Researchers found that the annual freeze of 26 bodies of water in North America, Asia, and Europe shifted later by about 8.7 days over the last one and a half century, while the spring ice breakup came about 9.8 days earlier. The study reported very strong evidence of a general warming from 1845 to 1995 in areas where there is ice cover. The change in the ice-on and ice-off days found in the study corresponds to an air temperature warming of about 1.8 °C over the past 150 years.

However, over the last century, a decrease of nearly 10 % snow cover and a 10–15 % decrease in spring and summer sea ice in the Northern Hemisphere have been witnessed. Other changes linked to climate include longer growing seasons, increases in rainfall and rainfall intensity in the Northern Hemisphere, and shifts when ice freezes and breaks up on rivers and lakes. The IPCC has projected that global average surface temperatures could increase by 1.4–5.8 °C by 2100. Daily minimum temperatures as well as the number of hot days, with less cold and frosty days will increase (Parry 2007).

The primary driver of climate change impacts on water resources is temperature. Current climate models suggest that effects of temperature increases are felt throughout the climatic regime leading to hydrological changes (e.g., seasonal redistribution and duration of rainfall) and other related impacts. These hydrological changes are manifested as periods of increased rainfall or floods as well as periods of drought. In addition to precipitation effects, increased temperatures are impacting glacier and snowmelt patterns, while also creating more extreme hurricane or typhoon conditions with associated high winds.

The global average precipitation and evaporation are also expected to increase by about 1–9 %. The precipitation changes are expected to vary from region to region, with increases over the northern mid- to high latitudes and in Antarctica during the winter. The intensity of extreme weather events is also likely to increase with greater extremes of both flooding and drought. Precipitation, temperature, and carbon dioxide levels can affect the demand for water as well as the supply.

Relationship and Degree of Elasticity Between Climate Change and Water Resources

Water resources are important to both the society and the ecosystems. The biology depends on a reliable supply of clean drinking water to sustain the health. We also need water for agriculture, energy production, navigation, recreation, and manufacturing. Many of these uses put pressure on water resources, stresses that are likely to be exacerbated by climate change. So, as temperatures rise, people and animals need more water to maintain their health and thrive. Many important economic activities, like producing energy, raising livestock, and growing food crops, also require water. The amount of water available for these activities may be decreased as the Earth warms and if the competition for water resources increases.

In many areas, climate change could increase water demands while shrinking water supplies. This shifting balance would challenge water managers to simultaneously meet the needs of growing communities, sensitive ecosystems, farmers, ranchers, energy producers, and manufacturers. In some areas, water shortages will be less of a problem than increases in runoff, flooding, or sea level rise. These effects can deteriorate the quality of water and can damage the infrastructure that is used to transport and deliver water.

Hydrological Variables

The water cycle is a delicate balance of precipitation, evaporation, and all of the steps in between. Warmer temperatures promote evaporation of water into the atmosphere, thus increasing the atmosphere capacity to “hold” water. Increased evaporation may dry out some areas and cause excess precipitation on other areas.

Climate warming observed over the past several decades is consistently associated with changes in a number of components of the hydrological cycle and hydrological systems such as changing precipitation patterns, intensity and extremes, widespread melting of snow and ice, increasing atmospheric water vapor, increasing evaporation, and changes in soil moisture and runoff. There is significant natural variability on interannual to decadal timescales – in all the components of hydrological cycle, often masking long-term trends. There is still substantial uncertainty in trends of hydrological variables because of large regional differences and because of limitations in the spatial and temporal coverage of monitoring networks (Huntington 2006).

The hydrology of arid and semiarid areas is particularly sensitive to climate variations. Relatively small changes in temperature and rainfall in these areas could result in large changes in runoff, increasing the likelihood and severity of droughts and/or floods.

Precipitation

Here the word precipitation includes rainfall, snowfall, dews, etc. There is a direct influence of climate change and global warming on precipitation. Increased temperature leads to greater evaporation and thus surface drying, thereby increasing the intensity and duration of drought as well as precipitation elsewhere. However, the water-holding capacity of air increases by about 7 % per 1 °C warming, which leads to increased water vapor in the atmosphere. Hence, storms (individual thunderstorms, extratropical rain or snowstorms, tropical cyclones) supplied with increased moisture could produce more intense precipitation events. Such events are observed widely occurring, even where total precipitation is decreasing. This increases the risk of flooding. The atmospheric and surface energy budget plays a critical role in the hydrological cycle and also in the slower rate of change that occurs in total precipitation than total column water vapor. With modest changes in winds, patterns of precipitation do not change much but result in dry areas becoming drier (generally throughout the subtropics) and wet areas becoming wetter, especially in the mid- to high latitudes: the “rich get richer and the poor get poorer.”

This pattern is simulated by climate models and is projected to continue into the future. With warming, more precipitation occurs as rain instead of snow, and snow melts earlier; there is increased runoff and risk of flooding in early spring but increased risk of drought in summer, especially over continental areas. However, with more precipitation per unit of upward motion in the atmosphere, the atmospheric circulation weakens that results monsoons to falter. In the tropics and subtropics, precipitation patterns are dominated by shifts as sea-surface temperatures change (El Niño is a good example).

Although the precipitation has increased by 0.5–1 % per decade during the twentieth century, over most mid- and high latitudes of the Northern Hemisphere continents, and the rainfall has increased by 0.2–0.3 % per decade over the tropical (10°N to 10°S) land areas, rainfall has decreased over much of the Northern Hemisphere subtropical (10°N to 30°N) land areas during the twentieth century by about 0.3 % per decade (this is the region in which most of Pakistan is situated) (Imtiaz 2002; Rangwala and Miller 2012).

Most models simulate precipitation that occurs prematurely and too often and with insufficient intensity, resulting in recycling that is too large and a lifetime of moisture in the atmosphere that is too short, which affects runoff and soil moisture (Trenberth et al. 2007).

Evapotranspiration

There are very limited direct measurements of actual evapotranspiration over global land areas (Fig. 1). Decreasing trends during recent decades are found in sparse records of pan evaporation (measured evaporation from an open water surface in a pan, a proxy for potential evapotranspiration) over the entire globe. Using observations of precipitation, temperature, cloudiness-based surface solar radiation, and a comprehensive land surface model, Qian et al. (2006) found that global land evapotranspiration closely follows variations in land precipitation. Changes in evapotranspiration depend not only on moisture supply but also on energy availability and surface wind. Other factors affecting actual evapotranspiration include the direct effects of atmospheric CO₂ enrichment on plant physiology.

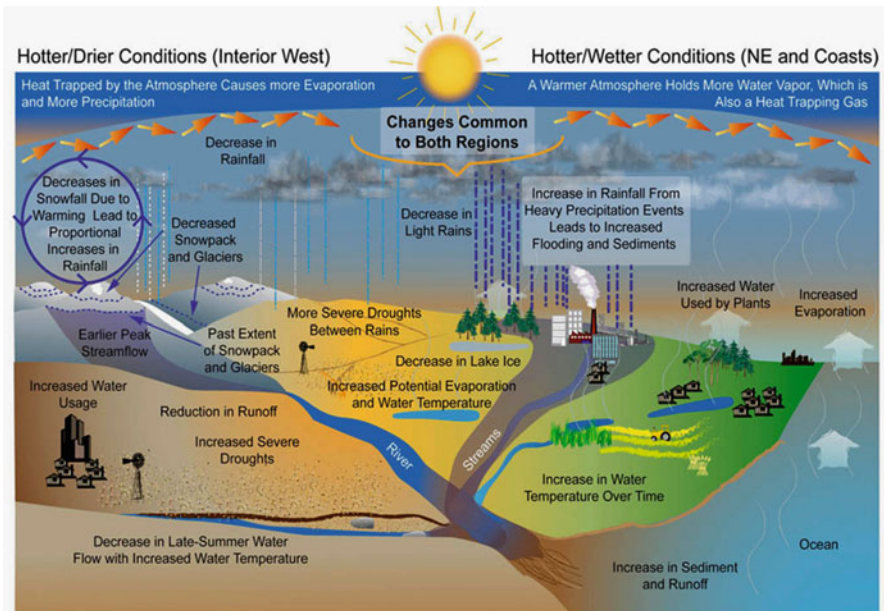


Fig. 1 Projected impacts of climate change on the hydrological cycle (Source: Karl et al. 2009)

Evaporative demand or “potential evaporation” is projected to increase almost everywhere. This is because the water-holding capacity of the atmosphere increases with higher temperatures, but relative humidity is not projected to change markedly. Resultantly, water vapor deficit in the atmosphere increases as does the evaporation rate (Trenberth et al. 2003).

Runoff

With an increase in precipitation (rain, snow, dew, etc.) and more snow melts earlier, there is increased runoff and risk of flooding in early spring with increased risk of drought in summer in dry areas. Climate change could cause more and intense precipitation but sporadic which is likely to be offset by the increased evaporative demand in many regions of South Asia and the world, i.e., where intense rainfall events with high runoff are interspersed with long dry periods of increased evaporation and transpiration.

Soil Moisture

Soil moisture is a source of thermal inertia due to its heat capacity and the latent heat required for evaporation. Soil moisture has been proposed as an important control on summer temperature and precipitation. Surface water balances reflect the availability of both water and energy. In regions where water availability is high, evapotranspiration is controlled by properties of both the atmospheric boundary layer and surface vegetation cover. Changes in the surface water balance can feed back on the climate system by recycling water into the boundary layer (instead of allowing it to run off or penetrate to deep soil levels). Changes in soil moisture depend on alterations in volume and timing not only of precipitation but also of evaporation which indirectly is affected by vegetation. The sign and magnitude of such effects are often highly variable depending on the details of the local environment (Bates et al. 2008).

Impacts of Climate Change on Surface Water Resources: Water Quantity and Availability

Excessive water uses put pressure on water resources, stresses that are likely to be exacerbated by climate change. In many areas particularly dry areas, climate change is likely to increase water demand while shrinking water supplies. This shifting balance would challenge water managers to simultaneously meet the needs of growing communities, sensitive ecosystems, farmers, ranchers, energy producers, and manufacturers. Climate change impacts on surface water (quantity and availability) vary greatly as discussed in the following sections.

Floods

Floods depend on a number of non-climatic factors like existence of dams or dikes. However, there are indications that climate change impacts their intensity and

frequency. These flood-producing processes include intense and/or long-lasting precipitation, snowmelt, dam break, and decreased conveyance due to ice jams or landslides or by storm. Floods depend on precipitation intensity, volume, timing, phase (rain or snow), antecedent conditions of rivers, and their drainage basins (e.g., presence of snow and ice, soil characters, wetness, rate and timing of snow/ice melt, urbanization, existence of dikes, dams, and reservoirs). Human encroachment into recent and subrecent flood plains and lack of flood response plans increase their damage potential.

Globally, the number of great inland flood catastrophes during 1996–2005 is twice as large per decade as between 1950 and 1980. Based on climate models, the area flooded in Bangladesh is projected to increase by at least 23–29 % with a global temperature rise of 2 °C (Bates et al. 2008). This has been associated with an increasing frequency of heavy precipitation events; no ubiquitous increase is visible in trends in high river flows. With increased intensity and irregularity of rainfall, the interannual variability of river flows is likely to increase, such that rivers will become increasingly “flashy” and seasonal. As a result, flood events will be more common, and an increased proportion of the available surface water will be lost in peak discharges, decreasing the quantity of accessible water (Parry 2007).

Drought

Drought is a normal, recurrent climatic feature which has caused distress since the known history of mankind. The term drought may refer to a meteorological drought, hydrological drought (low river flows and low water levels in rivers, lakes, and groundwater), agricultural drought (low soil moisture), and environmental drought (a combination of the above). The socioeconomic impacts of droughts may arise from the interaction between natural conditions and human factors such as changes in land use, land cover, and the demand for and use of water. Excessive water withdrawals can exacerbate the impact of drought.

Droughts have become more common, especially in the tropics and subtropics, since the 1970s. Pakistan has been suffering serious droughts periodically due to below normal rainfall. Although drought affects nearly all the climatic regimes and has pronounced consequences in both developed and developing countries, its effects are noticeably devastating in developing nations like Pakistan where rain-fed farming covers considerable area. Assessing the onset of drought, extent, intensity, and duration can limit drought-induced impacts and can provide a base to develop an effective drought mitigation response. Previous drought events in dry areas and the magnitude of drought losses indicate the continuing vulnerability of dry areas to drought due to lack of contingency planning. The integration of existing drought monitoring tools for dry areas is essential to decrease the vulnerability of drought in these regions. In order to reduce vulnerability to drought event in Pakistan, it is inevitable to assess relevant effects and identify their potential reasons. Due to spatial and temporal variability, it is imperative to enhance the data availability for mapping and monitoring this phenomenon. Drought-related

multidisciplinary information can be handled by using geographic information system (GIS). Government institutions look after potential drought-stricken victims and others living in potential drought areas by using spatial analysis in GIS that can lead to a decision support system (Anjum et al. 2012).

Surface Water Runoff and River Discharge

The most dominant climatic drivers for runoff and river discharge are precipitation, temperature, and evaporative demand (Parry 2007). More precipitation brought about by more intense but sporadic rainfall events is likely to be offset by the increased evaporative demand in many regions of South Asia and the world, particularly where intense rainfall events with high runoff are interspersed with long dry periods of increased evapotranspiration. These conditions may lead to a greater risk of drying, land degradation, low groundwater recharge, and a significant decrease in the amount of available surface water, which are already seasonal (Meehl et al. 2007). Changes in river flows as well as lake and wetland levels will also depend crucially on whether precipitation as snow or rain. By the end of this century, rivers in South Asia are likely to exhibit decreased summer flows (after an initial increase) and increased winter flows resulting from recession of the Himalayan ice mass in a warmer condition. Glacial melt water presently contributes up to 70 % of the dry season flow of the Indus, so glacial recession will have significant impacts on water availability in South Asia climate (Kundzewicz et al. 2007).

At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase in runoff and others experiencing a decrease in runoff.

Sea Level Rise

Global mean sea level is rising and the rate of rise has increased between the mid-nineteenth and the mid-twentieth centuries. The sea level increased about 18 cm (7 in.) during the past century. The most recent IPCC results suggest sea level might rise another 15–95 cm (6–37 in.) by the year 2100 owing to rise in temperature by 0.06 °C in the Atlantic, Pacific, and Indian Oceans (Parry 2007).

High sea levels and increased storm surges could adversely affect freshwater supplies to coastal areas. Saltwater in river mouths and deltas would advance inland and coastal aquifers and could induce threat of saltwater intrusion, jeopardizing the quality water for many domestic, industrial, and agricultural users. As the sea rises, saltwater will also move into freshwater areas. In addition, as more freshwater is removed from rivers for human use, saltwater will move farther upstream. Drought can cause coastal water resources to become more saline as freshwater supplies from rivers are decreased. Water infrastructure in coastal cities, including sewer systems and wastewater treatment facilities, faces risks from rising sea levels and the damaging impacts of storm surges.

Wildfire

Wildfire is a primary disturbance agent affecting the structure and composition of many forest ecosystems and hydrological cycle. The complex role that wildfire plays in shaping forests has been described in terms of vegetation responses as dependent on, sensitive to, independent of, or influenced by fire (Myers 2006). For example, fire is largely absent where cold, wet, or moist conditions prevail (e.g., tundra, some rain forests, and desert). At the other extreme, fire is essential where species have evolved to withstand burning and facilitate fire spread. Notable fire-dependent ecosystems include many coniferous boreal, temperate and tropical forests, eucalyptus forests, grasslands, savannas and marshes, and palm forests.

The specific weather conditions during a fire event greatly influence how the fire burns. It follows that long-term climate variability can influence fire behavior by affecting site-specific fuel conditions (fuel moisture, type and arrangement, and water availability). The fires we see today in some forest landscapes are of a much higher intensity than those at the turn of the twentieth century due to decades of fire suppression, an increase in biomass due to the post-1976 increase in southwestern rainfall (Swetnam et al. 1999) and warming temperatures coupled with intermittent drought conditions.

Climate change that results in drier, warmer climates has the potential to increase fire occurrence and may be affected due to the greenhouse effect. It is shown that future wildfire potential increases significantly in the United States, South America, Central Asia, Southern Europe, Southern Africa, and Australia. Fire potential moves up by one level in these regions, from currently low to future moderate potential or from moderate to high potential. It is suggested that dramatic increases in wildfire potential will require increased future resources and management efforts for disaster prevention and recovery (Liu et al. 2010).

Deforestation

The impacts of deforestation on climate illustrate this complexity. Some studies indicate that deforestation could lead to decreased daytime temperatures and increases in boundary layer cloud as a consequence of rising albedo, transpiration, and latent heat loss. However, these effects are dependent on properties of both the replacement vegetation and the underlying soil/snow surface. In some cases the opposite effects have been suggested.

Forests contribute to the regional water cycle, with large potential effects of land-use changes on local and regional climates. On the other hand, forest protection can have drought and flood mitigation benefits, especially in the tropics. The effects of deforestation on precipitation are likewise complex and could be both negative and positive, dependent on land surface and vegetation characteristics.

Impacts of Climate Change on Groundwaters

Up to 80 % of rural water supplies are dependent on groundwater, providing safe water for 400 million people. This dependence is likely to increase as surface water sources become increasingly seasonal and demands from domestic, agricultural, and industrial users for reliable water increase. Groundwater storage comprises approximately 100 times the surface water storage and provides an important buffer against climate variability and change (MacDonald et al. 2011).

Groundwater and soil moisture collectively account for over 98 % of the available global freshwater resources. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and during warm periods (Kundzewicz et al. 2007). Although groundwater systems are likely to respond more slowly to climate change than surface water systems, the impact of climate change on recharge, and hence long-term availability, remains unclear.

Climate change could modify groundwater recharge patterns as changes in precipitation and evaporation translate directly to shifts in soil moisture deficits and surface water runoff. Increases in rainfall intensity and evaporative demand would result in increased irregularity of groundwater recharge (Kundzewicz et al. 2007). However, groundwater recharge will also be affected by soil degradation and vegetation changes, both of which may be affected by climate and human drivers.

Limited information is available on groundwater conditions and trends, and present quantities and patterns of recharge of groundwater are uncertain. Moreover, long-term projections of rainfall and temperature reveal little about how groundwater recharge may change. Hydraulically effective rainfall contributing to groundwater recharge is affected as much by annual rainfall variation, the timing, intensity, and duration of rainfall events, as by total seasonal or annual amounts (Kundzewicz et al. 2007).

Impacts of Climate Change on Water Quality

Climate change affects water quality through both increased temperature and hydrological changes in rainfall affecting runoff and mobilization of nutrients and other pollutants. Heavy downpours increase the amount of runoff into rivers and lakes, washing sediment, nutrients, pollutants, trash, animal waste, and other materials into water supplies, making them unusable and unsafe. The increased water temperature will affect ice cover and circulation patterns in lakes and rivers as well as the rate of biogeochemical and ecological processes that determine water quality. In areas where river flow and groundwater recharge will decrease, water quality could deteriorate due to less dilution of pollutants. High intensity and frequency of floods and frequent extreme rainfall events increase the load of pollutants (organic matter, nutrients, etc.) washed from soils and overflows of sewage systems to water bodies. For example, in the northeast and midwest,

increases in heavy rainfall events caused problems for the water infrastructure, as sewer systems and water treatment plants were overwhelmed by the increased volumes of water (Grimalt et al. 2001). This may result in:

- (i) **Increased water temperature:** Since water temperature is mainly determined by heat exchange with the atmosphere, high air temperatures lead to high water temperatures. Water temperature may also be affected by other factors than air temperature. Especially in larger rivers, flow regulation, hot or cooling water from power plants, groundwater flow, extreme hydrological events, and high wind speed may be important (Moatar and Gailhard 2006).
- (ii) **Water color:** Due to increased input of humic substances as dissolved organic carbon (DOC) from the catchment and through water runoff, the coloring is induced.
- (iii) **Dissolved organic carbon (DOC):** Climatic factors may affect both concentrations and fluxes of DOC. These affect production of DOC in the terrestrial systems and thereby changing DOC concentration without changes in runoff. However, increased runoff may also affect DOC concentration through changing the degree of dilution and by altering water flow paths through soil. Drought and soil frost may also stimulate DOC production through increased fine root and microbial mortality, increased fragmentation of soil organic matter (SOM) and fresh litter, and increased aggregate instability, directly releasing DOC or increased microbial activity (Beltaos and Prowse 2009).
- (iv) **Oxygen content:** Increased biological respiration results in low DOC, particularly in summer low-flow periods and in the bottom layers of lakes. High temperature and low oxygen concentration will cause stress and may decrease the habitats of cold-water species like salmonid fish in lakes and rivers. The DOC concentration decreases as a direct result of temperature rise but also as an effect of increased respiration, either as a direct response to increased temperature or due to increased nutrient levels (Bloomfield et al. 2006).
- (v) **Increased nutrients:** Elevated mineralization and releases of nitrogen (N), phosphorus (P), and carbon (C) from SOM and increased runoff and erosion will result in increased nutrient loads. Release of P from bottom sediments in stratified lakes may increase due to declining oxygen concentrations in the bottom waters. A warmer climate can enhance the pollution load of nutrients to lakes and rivers to induce eutrophication. Changes in rainfall and resulting discharge patterns will also affect nutrient concentrations. Low summer flow will give less dilution of nutrients that affects higher nutrient concentration. High intensity and frequency of floods and more frequent extreme rainfall events will give increased surface runoff and erosion, increasing the nutrient load to the surface water. Heavy rainfall may account for a significant proportion of annual P transfer from agricultural soils under arable crops (Jeppesen et al. 2009).

- (vi) **Underwater light conditions:** These are mainly affected by three factors: turbidity, DOC concentration, and phytoplankton density. Climate may change the underwater light conditions through changes in erosion, affecting both turbidity and background input of nutrients, and through changes in the carbon cycling processes in the catchment affecting the input of humic substances. Moreover, if the stratification pattern of lakes are changed, the depth of the circulating water column will be affected and thereby also the mean underwater light for phytoplankton.
- (vii) **Salinization:** Increased erosion, runoff, and sewage discharge into water bodies could increase the concentration of salts in water which is highly hazardous to its inhabitants and users.
- (viii) **Pathogenic microbes:** Sewage overflows upon heavy rains combined with high water temperatures and long ice-free season may increase the number of pathogenic microbes in water. High intensity rainfall may also give increased input of pathogens from pastures, rangelands, grasslands, drains, and treatment plants. Statistically significant correlations have been observed between rainfall and outbreaks of waterborne disease in both plants and animals including human beings.
- (ix) **Hazardous substances:** Direct temperature effects will largely be limited to compounds which are volatile (organic pollutants, mercury) and/or subject to degradation processes. Climate change may affect future use of pesticides. It is not likely that changes in cropping patterns will affect the use of pesticides to a large extent. However, increased prevalence of existing pests, weeds, and diseases and increased pest resistance may lead to wider and more frequent application of pesticides and introduction of new products. On the other hand, in areas severely affected by drought, the decline in agriculture will lessen the use of pesticides. Increased temperature will increase the rate of dispersal and give wider distribution of pesticides (Bloomfield et al. 2006).

Climate change will also affect mineralization of previously released hazardous substances of soil and sediment. Increased frequency of intense rainfall events and floods will increase soil and sediment erosion and increase the pollutant concentration in aquatic systems (Bloomfield et al. 2006). More intense rainfall can also give more bypass flow and more rapid movement of pesticides from agricultural soils to surface water duly promoted by the negative change on soils. Loading of hazardous substances may increase due to sewage overflow and increased leaching of hazardous substances from urban surfaces resulting from increased rainfall.

Impacts of Climate Change on Water Resources of Pakistan

Pakistan is predominantly an arid and semiarid country. Pakistan is an agricultural country mainly dependent on surface irrigation through the Indus river system. The country has developed the world's largest contiguous canal network. According to the climate change scenario, the warming is reflected in the river-flow data of

Pakistan, especially during the 1990s. In the post-Tarbela era, water diverted from rivers to the canal system has remained constant around 104 MAF per year. The freshwater outflow to sea may, therefore, be considered a good indication of the total river flow for this period. From the year 1975–1990, average flow into the sea has been 34.13 MAF per year. However from the year 1990 to 2000, this flow has been 47.88 MAF a year, i.e., about 40 % greater. For the winter season for the same period, average flow into the sea from the year 1975 to 1990 was 1.86 MAF a year. However from the year 1990 to 2000, this flow was 3.28 MAF a year, i.e., about 76 % higher. Although other factors may also be contributing, nevertheless the change visible in this time frame is quite large which is partially due to climate change. The global warming initially caused the river flow to increase as glaciers melt, then decrease as these recede. One more fact that emerges from the data is that when there is an excessive amount of water in summer, the succeeding winter also has more water than usual; this increased water availability in winter seems due to increased rains because of local effect of greater moisture in the soils and atmosphere.

An overall increase in rainfall of 50–150 mm has been recorded in summer monsoon belt for the period 1931–1990. But a decrease in rainfall was witnessed in the rest of country. Such decrease is 50–100 mm in western and northern mountains, whereas it is 25–50 mm in the southeastern and central parts. These variations are in line with the predictions of global warming which is expected to cause drier south and wetter north.

Naheed and Rasul (2011) used rainfall variability coefficient to analyze the past time situation from 1960 to 2009. The results of the decadal analysis showed high value of the variability coefficient in Balochistan (251 %), Sindh (247 %), and Punjab (208 %) provinces of Pakistan. However the annual analysis showed the increasing trend of variability coefficient from north to south. According to the inter-seasonal analysis, variation in the coefficient of variability was higher in post-monsoon and pre-monsoon seasons compared to the winter and monsoon seasons. This analysis showed that forecasting is a challenging job where the variability is prominently high (Naheed and Rasul 2011).

Droughts in one country or region also affect neighboring regions that otherwise are supposed to make surplus water available for interbasin transfers during the flood seasons. Increase in persistency of drought requires a reexamination of our assumptions, operating norms, and contingency measures for existing and planned water management measures. Droughts produce additional burden of migration of population from neighboring regions into lands that are already stretched to the maximum. Besides the social disruptions, there is the cost of the degradation of the natural resources due to their over-exploitation.

Adaptation Measures and Recommendations

Adaptation refers to the adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects to reduce the vulnerability and build the resilience of ecological and social systems and economic sectors to

present and future adverse effects of climate change, which moderates harm or exploits beneficial opportunities (Parry 2007).

The relationship between adaptation and “normal” development is a subject of debate. Adaptation interventions often mirror ongoing efforts to promote sustainable development, making it hard to draw neat distinctions or, in terms of financing, to identify their incremental and/or additional cost over and above “development as usual.”

Decreasing the Vulnerability of Water Resources

Development of human societies has involved a continuous process of adapting to changing stresses and opportunities. While climate change is seen as a relatively recent phenomenon, individuals and societies are adapting to a range of environmental and socioeconomic stresses. Adaptation aims at decreasing unavoidable adverse impacts in the shorter term, lowering vulnerability to present climate variability, and exploiting opportunities provided by climate change. Adaptation includes proactive and reactive measures, which relate mainly to planned adaptation as well as autonomous actions. Mitigation aims at avoiding the unmanageable impacts, while adaptation aims at managing the unavoidable impacts. In many parts of the world, especially in semiarid lands, there is good experience with phenomenon such as drought. As climate extremes are predicted to increase the frequency and intensity in future, it is important to understand and learn from relevant past adaptations and indigenous knowledge. The criteria to select adaptation measures and options for water are presented in Tables 1 and 2, respectively.

Adaptation Measures for Water Sector

Climate change poses a challenge to water managers by introducing uncertainty in future hydrological conditions. It may also be very difficult to detect an underlying trend, i.e., adaptation decisions may have to be made before it is clear how hydrological regimes may actually be changing. Water management in the face of climate change, therefore, needs to adapt a scenario-based approach.

Water Management Measures

These efforts include a wide variety of activities based on current and anticipated climate change impacts. Specific adaptation approaches include:

- (i) Using water barrels that capture excess rainfall to minimize flooding and maintain a constant supply of water through dry spells
- (ii) Improving irrigation systems and their efficiency
- (iii) Protecting valuable resources and infrastructure from flood damage
- (iv) Managing rainfall on-site to limit contamination and protect water quality
- (v) Limiting development within vulnerable watersheds

Table 1 Criteria to select adaptation measures

Criterion	Sub-criterion	Guiding questions
Effectiveness of adaptation	Adaptation function	Does the measure provide adaptation in terms of decreasing impacts and exposure, enhancing resilience, or enhancing opportunities?
	Robustness to uncertainty	Is the measure effective under different climate scenarios and different socioeconomic scenarios?
	Flexibility	Can adjustments be made later if conditions change again or if changes are different from those expected today?
Side effects	No regret	Does the measure contribute to more sustainable water management and bring benefits in terms of alleviating the already existing problems?
	Win-win (or win-lose)?	Does the measure entail side benefits for other social, environmental, or economic objectives?
	Spillover effects	Does the measure affect other sectors or agents in terms of their adaptive capacity? Does the measure cause or exacerbate other environmental pressures?
Efficiency, costs, and benefits	Low regret	Are adaptation measures will bring high benefits relative to costs? (If possible, consider also distributional effects (e.g., balance between public and private costs) as well as nonmarket values and adverse impacts on other policy goals)
Framework conditions for decision-making	Equity and legitimacy	Who wins and who loses from adaptation? Who decides about adaptation? Are decision-making procedures accepted by those affected and do they involve stakeholders? Are there any distributional impacts of the climate change or of the adaptation measures?
	Feasibility of Implementation	What barriers are there to implementation?
		Technical
		Social (number of stakeholders, diversity of values and interests, level of resistance)
		Institutional (conflicts between regulations, degree of cooperation, necessary changes to current administrative arrangements)
Alternatives	Are there alternatives to the envisaged adaptation measures that would be less costly or would have fewer negative side effects?	
Priority and urgency	How severe are the climate change impacts the adaptation measure would address relative to other impacts expected in the area/river basin/country? When are the climate change impacts expected to occur? At what timescales does action need to be taken?	

Source: United Nations (2009)

Table 2 Some adaptation options for water supply and demand

Supply side	Demand side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping pattern, crop mix, irrigation methods, and area planted
Desalination of seawater	Reduction in water demand for irrigation by importing agricultural products
Expansion of rainwater storage	Promotion of indigenous practices for sustainable water use
Removal of invasive nonnative vegetation from riparian areas	Expanded use of water markets to reallocate water to high value uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

Source: Parry (2007)

- (vi) Precise weather forecasting and information network for farmers
- (vii) Information exchange on new technologies at national and international levels
- (viii) Managing aquifer recharge (MAR) is a technique for arid regions to replenish aquifers and allow subsequent recovery of water for urban, agricultural, and environmental benefit

Water Conservation Measures

Water conservation is an integral part of managing water resources. For regions experiencing population growth, water conservation can adjust current water use patterns to maximize existing water supplies. Water conservation can be achieved in several ways, varying greatly in terms of complexity, cost, and water quantity such as:

- (i) Ensuring water conservation, lowering irrigation system losses, and providing incentives for adoption of more efficient irrigation techniques
- (ii) Conserving water and minimizing runoff with climate-appropriate landscaping, such as xeriscaping
- (iii) Promoting local watershed management systems
- (iv) Expand floodplain areas, emergency flood reservoirs
- (v) Introducing local rainwater harvesting measures
- (vi) Efficient urban and industrial wastewater reuse

Upgrading Infrastructure

Upgrades and maintenance of water distribution and storage systems are among the most effective methods those can be employed for water conservation. Increase the capacity of existing water reservoirs (dams) and develop new ones for increasing water storage. Infrastructure upgrades consist of identifying and repairing leakages, conducting pressure adjustments, replacing aging infrastructure, and developing new ones within the existing urban water distribution system.

Exploring Alternative Water Resources

Desalination could provide an unlimited source of water. Saltwater desalination is a process of stripping salt, minerals, or other chemical entities from seawater to produce potable water. While the possibility of an unlimited supply is appealing, there are also various downsides associated with desalination. Though there are other desalinating technologies, we considered reverse osmosis (RO) desalination due to its increasing dominance worldwide. Recycling and reuse of municipal wastewater is also an effective source. Due to low precipitation and lack of perennial streams in dry areas, the most reliable water source for irrigation and industries is recycled wastewater.

Domestic Fixtures

Kitchens, toilets, sinks, and showers account for approximately 60 % of domestic water use on an average, so installation of water saving fixtures can significantly lower household water consumption. Therefore, for future generations implementation of water-efficient fixtures should be taken into account in new construction projects. We should also focus on water saving from a combination of fixtures at domestic level through public awareness.

Measures for Water Quality Control

All possible adaptive measures should be focused to prevent water pollution. All water management and conservation measures concentrated on decreasing runoff and floods should be adopted to minimize the entry of sediments, nutrients, pollutants, contaminants, trash, animal waste, sewage effluent, and other materials into water bodies and supplies; these could make waters unusable, unsafe, or in need of water treatment. Since higher intensity and frequency of floods and more frequent extreme rainfall events are expected to increase, the load of pollutants (organic matter, nutrients, and hazardous substances) washed from soils and overflows of sewage systems to water bodies (Grimalt et al. 2001). Four concrete water quality control aspects can be explained as:

- (i) Measures for point source pollution control
- (ii) Wastewater treatment and recycling
- (iii) Measures for nonpoint source (agricultural) pollution control
- (iv) Ecological restoration and eco-hydrology

(i) Measures for Point Source Pollution Control

Sewage treatment plants are one of the main sources of control. The main pollution problems associated with point pollution discharges are high temperature, organic and inorganic pollutants, and nutrients (nitrate, P, etc.). Uncontrolled or accidental discharge of untreated wastewaters into water bodies is particularly problematic from an environmental perspective, due to

its high levels of nutrients. The risk of this kind of discharge is particularly high in sewerage systems which combine storm water and wastewater; overflows of the system into water bodies, due to flash floods, for instance, can contain important amounts of untreated wastewater and several pollutants.

The decrease in point source pollution in view of these discharge pollutants is an effective adaptation measure. These types of measures are also recommended for limiting the risk of eutrophication in lakes, specifically targeting nutrient loading from point sources. In addition to environmental benefits, the measure has clear additional benefits for human health.

These include:

(a) **Nitrate and phosphate load in wastewaters**

The N and P present in wastewaters can lead to eutrophication of surface waters. Climate change increases this risk due to low river flows and increased frequency of flash floods – with increased storm and sewage overflow – predicted for some regions. One measure addressing this is banning or minimizing of phosphate in relevant domestic products and industrial processes. Phosphorus reclamation is considered an effective solution for maintaining high water quality in a changing climate and delivering economic benefits at the same time.

(b) **Separation of rainwater and sewage**

Untreated wastewater reaching surface waters constitute a serious pollution problem. A possibility, both when building new canalization and renovating existing drainage, is to separate wastewater and storm water. This is a comparatively expensive option, but it will strongly lower the risk of untreated wastewater entering the water systems.

(c) **Improvement of wastewater infrastructure capacity**

In many regions, the frequency of flash floods is expected to increase due to climate change. Improvements in the capacity of treatment plants or in storage capacity can address this problem.

(d) **Incorporating climate change considerations into discharge licensing schemes**

New forms of discharge license agreements include provisions that address uncertainty due to climate change. Licenses from point source discharges should be reviewed periodically; changes related to climate change impacts as well as in other parameters such as population behavior and available technology can thus be reflected in the revised agreements. In the United Kingdom, discharge licenses of wastewater treatment plants are reviewed every 5 years to this purpose. Changes to the system's carrying capacity to address climate change will be reflected in the pollution load the system is allowed to take up.

(ii) **Wastewater Treatment and Recycling**

Sewage treatment plants are one of the main control measures of point pollution. Uncontrolled or accidental discharge of untreated wastewaters into water streams is particularly problematic from an environmental

perspective due to its high levels of nutrients and other toxic substances. Such discharge is particularly high in sewerage systems which combine storm water and wastewater. They also overflow system into water bodies due to flash floods and can contain significant amounts of untreated wastewater and pollutants. Both domestic and industrial wastewater treatment and agricultural wastewater treatment and seawater treatment are effective measures for pollution control. The treated water reuse for drinking, irrigation, or industrial processes is also a potential adaptive practice.

(iii) **Measures for Diffuse Pollution Source Control**

Agriculture is the main source of diffuse pollution affecting water bodies. Conventional agriculture implies a certain level of leaching or washout of nutrients and pesticides, either to surface waters or to groundwater. Some pollutants (P, metals) adhere to soil particles and could reach surface water bodies as soil particles are transported due to erosion. Vegetated and unfertilized buffer zones alongside water courses act as a shield against overland flow from agricultural fields and decrease runoff from reaching the water course, thus decreasing erosion and the movement of pollutants into water courses.

Agricultural measures that limit erosion and leaching and aim at water conservation decrease the input of solid and suspended particles into water bodies and consequently the input of diffuse agricultural pollutants. These measures also have the potential of lowering the runoff from agricultural fields. Some of these measures are discussed in section “[Adaptation Measures for Agriculture Sector.](#)”

(iv) **Ecological Restoration and Eco-hydrology**

Identify the ecosystems that are most vulnerable to climate risk and then the best available measure on climate-induced impacts to engage with vulnerable groups including assessment hazards, vulnerabilities, and capacities that can support adaptation planning (Reid and Huq 2007). Adapt appropriate measures to preserve the ecology of risk areas.

Policy Measures

- (a) Assess and address the needs for additional water storage and distribution of infrastructure.
- (b) Ensure early rehabilitation, remodeling, and upgrading of the existing irrigation infrastructure in the country to make it resilient to climate change-related extreme events.
- (c) Identify new potential dam sites to keep the option open to develop new dams, should they be needed.
- (d) Develop necessary infrastructure to harness the potential of hill torrents.
- (e) Enforce measures to enhance the life of existing storage facilities.
- (f) Thus, policy coherence with the agricultural policy’s provisions should be ensured with regard to adaptation objectives in water management.

Integrated Water Resource Management

- (a) Ensure that, in making water allocations (within gross national availability) to various sectors in the medium to long term, due consideration is given to changes in sectoral demands caused by climate change.
- (b) Protect groundwater through management and technical measures such as regulatory frameworks, water licensing, slow action dams, artificial recharge especially for threatened aquifers, and adoption of integrated water resource management concepts.
- (c) Ensure rational groundwater exploitation by avoiding excessive pumping.
- (d) Ensure recycling of wastewater through proper treatment and its reuse, for example, in agriculture, artificial wetlands, and groundwater recharge.
- (e) Protect and preserve water catchment areas and reservoirs against degradation, silting, and irrigation system contamination.
- (f) Encourage active participation of farmers in water management along with line departments by accelerating implementation of participatory irrigation management reforms.
- (g) Ensure water distribution among provinces as far as possible in accordance with crop sowing timings.
- (h) Address seawater intrusion into the coastal region by allocating the requisite water flow downstream.
- (i) Take appropriate measures to preserve the ecology of dry river reaches.
- (j) Develop contingency plans for short-term measures to adapt to water shortages that could help mitigate drought.
- (k) Explore the possibility of joint watershed management of trans-boundary catchment areas with neighboring countries.
- (l) Safeguard Pakistan's rights on trans-boundary water inflows according to international norms and conventions.
- (m) Promote integrated watershed management including ecological conservation practices in uphill watersheds.

Legislative Framework

- (a) Legislate and enforce industrial and domestic waste management practices to protect the environment, in particular water resources, from further degradation.
- (b) Enact and enforce laws and regulations required for efficient water resource management and a groundwater regulatory framework.
- (c) Protect the Hindu Kush-Himalayan (HKH) glaciers, considered the world's water tower, by declaring them as "protected areas" through agreements among countries sharing the Himalayan region.

Adaptation Measures for Forests

- (i) Pest control: The biological control of forest pests is a very important adaptation measure.
- (ii) Promote farm forestry.
- (iii) Special attention should be given to those tree species which have poor seed production and dispersal, occupy ecological niches, have small populations and restricted ranges, and are peripheral.
- (iv) Preservation of watersheds to control sediments downstream.
- (v) Control of wastage as the use of waste wood to produce composite wood (Joseph and Tretsiakova-McNally 2010).

Adaptation Measures for Agriculture Sector

Agriculture is a sector that can make large contributions to adaptation to climate change and water quantity as well as quality. The following measures should be promoted:

- (i) **Support for switching to organic farming**
Organic farming strongly limits the possibility of agriculture-related pollution entering groundwater or surface water bodies. In addition to restrictions typically prohibiting the use of pesticides and fertilizers and regulating the use of natural fertilizers, requirements also typically include rules for improved soil structure and functioning, thus reducing the risk of soil erosion and unwanted sediment transport.
- (ii) **Precision farming**
Precision farming is based on the principle of meeting crop requirements as precisely as possible, using high technology (Global Positioning System yield mapping, variable rate delivery of seed, pesticides, and fertilizers) at a very fine scale (a few square meters) and aiming for application at the best possible moment in time. This results in maximization of efficiency of all inputs and reduces the risk of nutrient and pesticide runoff to surface water, leaching to groundwater, etc.
- (iii) **Erosion reduction measures**
 - (a) **Continuous plant cover (catch crops, intercrops)/winter plant cover:**
A cover crop will take up residual nitrate (NO_3^-) and other nutrients from soils and help stabilize soil thus decreasing soil erosion and the mobilization of associated pollutants.
 - (b) **Green stripes between fields:** Establishment of green stripes of some meters wide between agricultural fields, either with permanent or with temporary (yearly) cover crops, could decrease the erosion of field soil and surface runoff, thus the input of nutrients and pesticides into surface waters.

- (c) **Mulch sowing:** Maintaining plant parts after removing seed within the soil and abstaining from the use of ploughs naturally creates a protective layer of mulch while new plants are sowed directly into the soil. This helps maintain organic matter and preserve good soil structure, thus improving infiltration and retention of water and thereby decrease erosion and pollutant concentrations in surface runoff.
- (d) **Preventing soil compaction:** Soil compaction lowers water infiltration into soils, thus favoring surface runoff and erosion; compaction-free soils are also more drought resistant for crops. Options for preventing compaction include use of low ground pressure tires or tracks on vehicles, avoiding wet soils, and adding organic matter to soil.

Agricultural measures that decrease erosion and/or aim at soil conservation lower the input of solid and suspended particles and pollutants into water bodies. Some of these measures (e.g., winter plant cover) also absorb soil nutrients, reducing the nutrient load available for leaching. The measures also have the potential of strongly limiting the runoff from agricultural fields.

(iv) **Fertilizer, manure, and slurry management measures**

A rational and planned application of fertilizers/manure/slurry, which is well timed and which takes account of local parameters such as soil type and structure, is a widespread tool for reducing nutrient leaching and can have an enormous impact on water quality. These management measures include:

Nutrient balance: Nutrient balance spreadsheets inform farmers on the efficiency of nutrient utilization and help identify the cropping phases in which nutrients are lost. These help to accurately account for fertilizer use and decrease unnecessary nutrient inputs. The reductions have positive effects on both surface and groundwaters.

Manure application techniques: These involve, for instance, cutting slots in soil, injecting slurry, and then closing these slots after application. These lower groundwater and surface water pollution from NO_3^- leaching and phosphate runoff.

Integration of fertilizer and manure nutrient supply: Determining the amount of nutrients supplied to soils during manure application helps farmers judge the amount and ideal timing of additional fertilizers required by the crop. Taking better account of the nutrients contained in manure can reduce the need for fertilizer inputs, which in turn minimizes NO_3^- and P losses.

(v) **Risk-based fertilizer and manure restrictions**

Risk areas include areas with flushes draining to a nearby water course, cracked soils over field drains, or fields with a high P index. By avoiding the spreading of mineral fertilizers or manure at high-risk times, the NO_3^- leaching and loss of P through surface runoff is diminished. High-risk times include when there is a high risk of surface flow and rapid movement to field drains from wet soils or when there is little or no crop uptake.

(vi) Precision techniques

Additional options include the adoption of improved precision techniques such as soil analysis, manure analysis, adaptation of fertilizer and pesticide application on demand, matching fertilizer to seasonal conditions, and slow- and controlled-release fertilizers.

Cash Crops

Cash crops are usually sown after the harvest of one crop and before the sowing of the next. They offer forage or green manure (providing fertility for the soil thereby reducing N applications for the next crop) potential and are usually based on quick growing plants that will establish before winter. Their mitigation benefits include reducing N₂O emissions or leakage, improving N-use efficiency and carbon sequestration in the soil (Lal 2008).

Cropping Patterns

- Adjusting cropping pattern with water availability and water conservation
- More share of cropped area under oil seed crops and crops having less water requirement
- Improving productivity and production management
- Promoting farm forestry

Effective Irrigation Systems

Ensure water conservation, decrease irrigation system losses, and provide incentives for adoption of more efficient irrigation techniques:

Conserving water and minimizing runoff with climate-appropriate landscaping, such as xeriscaping, striping, or contouring
Improving irrigation systems and their efficiency
Improving water-use efficiency by recycling water

Strategies for Implementing Adaptation Measures

To maintain water supply and conservation as well as successful adaptation programs, the main strategies could be:

- (i) Research initiatives
- (ii) Planning and policies
- (iii) Public awareness
- (iv) Enhancing capacity
- (v) Technology transfer
- (vi) Follow-up programs after field demonstration by experts

The following measures should be adopted regarding this aspect:

- (a) Develop and extend water-efficient technologies and techniques for seawater utilization, water recycling, and avoiding wasteful use of domestic and drinking water.
- (b) Ensure measurement and monitoring of irrigation water delivery at various points of the supply system for effective planning and management.
- (c) Enhance national capacities in remote sensing and GIS techniques for monitoring temporal changes in glaciers and snow cover.
- (d) Enhance national capacities for making seasonal hydrometeorological forecasts, particularly for monsoon rainfall.
- (e) Prepare a comprehensive inventory of all water resources, including surface and groundwater, in order to support an efficient water management system in the country.
- (f) Strengthen the current hydrological network to monitor river flows and flood warning systems.
- (g) Devise and strengthen coordination mechanisms among national and international water sector institutions.
- (h) Promote public awareness campaigns to underscore the importance of conservation and sustainable use of water resources.
- (i) Enhance research activities and facilities regarding these aspects to accelerate adaptation.
- (j) Linking science, management, and policy in climate change and water resources.
- (k) Cost-effective, adaptive water management and technology transfer to all stakeholders.
- (l) Capacity building and institutional strengthening.
- (m) International and regional cooperation.

Mechanisms to Achieve Solutions

- (i) **Education and awareness:** Goals of education and awareness building efforts, connecting people to water quality impacts, documenting the problem, engaging the community, working with the media, and advocacy with policy makers and agencies.
- (ii) **Monitoring/data collection:** Problems with water quality data.
- (iii) **Governance and regulation:** Water reforms, policies, laws, and regulations; establishing water quality standards; international water quality guidelines; international governance and law; managing trans-boundary waters; financing water quality; institutional capacity building; and strengthening enforcement.
- (iv) **National strategies:** Provide the framework for adaptation actions, many of which have to be implemented at subnational and local levels. The relevance of adaptation at the national level is primarily concerned with coordinating information sharing and encouraging an appropriate, proportionate, and

integrated implementation of adaptation measures at different levels. The integration of adaptation into national sectoral policies and structural/cohesion funds together with fostering research and involving stakeholders are key instruments in this respect (Shardul and Samuel 2008).

Implications for Adaptation Process

It is possible to define five different types of limits on adaptation to the effects of climate change (Parry 2007):

- (i) Physical or ecological: It may not be possible to prevent adverse effects of climate change through technical means/institutional changes, e.g., it may be impossible to adapt where rivers dry up completely.
- (ii) Technical, political, or social: It may be difficult to find acceptable sites for new reservoirs or water users to consume less.
- (iii) Economic: An adaptation strategy may simply be too costly in relation to the benefits achieved by its implementation.
- (iv) Cultural and institutional: These may include institutional context within which water management operates, the low priority given to water management, lack of coordination between agencies, tensions between different scales, ineffective governance, and uncertainty over future climate change; all act as institutional constraints on adaptation.
- (v) Cognitive and informational: Water managers may not recognize the challenge of climate change or may give it low priority compared with other challenges. A key informational barrier is the lack of access to methodologies to cope consistently and rigorously with climate change.

Feedbacks from Adaptations to the Global Environment

In attempting to adapt implementation systems to cope with climate and other environmental changes, it will be important to ensure that changes proposed do not exacerbate climate change or other aspects of environmental degradation. Past intensification (land cover change, especially the removal of trees) has made a large contribution to CO₂ emissions. Hence one means of mitigating further greenhouse gas emissions is to intensify vegetation production on existing cleared areas and leave forests intact.

A series of adaptation measures are under way to counteract these negative impacts, such as improved point source control and measures to decrease nonpoint pollution especially agricultural measures, change of industrial processes to lessen effluents, banning P in detergents, and restoration measures in rivers and lakes. The uncertainty is whether these will be sufficient and be implemented soon enough to prevent these negative impacts on the inland waters of globe.

Conclusions

The aim of this chapter was to provide an overview of the climate change impacts on water resources in dry regions and propose possible adaptation measures to mitigate these impacts. Climate change drivers directly or indirectly affect water availability by altering precipitation patterns, increasing evaporation and atmospheric water vapor, melting glacier snow and ice, raising sea level, and causing changes in soil moisture, groundwater recharge patterns, surface runoff, and river discharge.

Climate change also result in significant deterioration of water quality by altering physical, chemical, and biological characteristics of water, thereby leading to a load of pollutants including sediments, salts, organic matter, nutrients, hazardous substances, and pathogens. Changes in the water resources lead to impacts on all the socioeconomic features such as energy production, infrastructure, food availability, health, agriculture, and environment.

A number of approaches, including water management and conservation, infrastructure upgrading, exploring alternate resources, and recycling wastewater, have been proposed to facilitate the adaptation planning and implementation process. In terms of water quality, all potential management, conservation, and control measures for both point and nonpoint sources should be adopted to minimize the entry of pollutants and contaminants into water bodies and supplies.

Extending access to reliable and affordable water in terms of quantity and quality remains key to strengthening livelihoods and building resilience to climate change. Therefore, it is need of the hour that an effective adaptation program through all potential integrated measures at local, national, and global scales should be initiated or enhanced under current and future water scarcity circumstances.

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