# 7 Climate Change, Water Resources, and Agriculture: Impacts and Adaptation Measures

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**Abstract**

Agriculture is one of the key domains that is significantly affected by climate change. The chapter presents the observed and projected impact of climate change on freshwater resources globally. In addition to this, case studies of successful implementation of adaptation measures adopted to tackle climate change-induced water stress in agriculture have been discussed with a special focus on high-altitude farming systems particularly vulnerable to increasing climate risk. As one of the potential adaptation measures, the relevance of water footprint as a tool to optimize water use and strategize cropping patterns with respect to crop water use efficiency and prevailing climatic conditions has also been discussed.

**Keywords**

Climate change · Freshwater resources · Water footprint · Agriculture · Adaptation · Irrigation water policy

## 7.1 Introduction

The water cycle is dynamic and intimately connected with atmospheric temperature and radiation balance. "*Changes in the large-scale hydrological cycle like increasing atmospheric water vapor content; changing precipitation patterns, intensity, and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff have been linked to the observed warming over the past several decades*" (Bates et al. 2008). Such climate-driven changes in the hydrological cycle along with non-climatic drivers of change such as population growth,

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economic development, urbanization, land use changes and water management responses can lead to diverse impacts and risks (Cisneros et al. 2014). Agriculture is one of the important sectors where changes in the hydrological cycle will have greater impact. It is among the most vulnerable sector to the risks of climate change (Smit and Skinner 2002). Both rainfed and irrigated agriculture are affected by climate-induced changes in precipitation and the availability of water. Climatic drivers are conditioned by and interact with non-climatic drivers which challenge the sustainability of resources. The significant role of non-climatic drivers in altering water supply and demand indicates that adaptation practices hold potential to improve the availability of water in the future (Cisneros et al. 2014).

Precipitation, temperature and evaporative demand are the most dominant climate drivers for water availability. Of these, temperature is predominantly significant in snow-covered basins and coastal areas where sea level rise due to high-temperature-induced expansion of water poses a threat. Groundwater tables and recharge rates are also affected by climate change through hydrological drivers that charge and recharge groundwater. Changes in permafrost thaw, surface water flow and precipitation variability also affect groundwater levels (IPCC 2007b). Table 7.1 presents the highlights of climate change-induced risks for freshwater resources and projections based on IPCC (Intergovernmental Panel on Climate Change) AR 4 (4th Assessment report) and AR 5 (5th Assessment report). Table 7.2 presents a few examples of the observed effects on freshwater water resources mainly attributable to climate change. The next section describes the effects of climate change on different hydrological variables that serve as sources of freshwater.

## 7.2 Impact of Climate Change on Freshwater Resources

### 7.2.1 Cryosphere

The cryosphere, derived from the Greek word “krios” meaning cold, is the frozen water part of the Earth system. The cryosphere consists of (a) ice and snow on land and (b) ice on water. Ice and snow on land include continental ice shelves, ice caps, glaciers and areas of snow and permafrost and stores around 75% of world’s freshwater whereas ice on water includes frozen parts of oceans, rivers and lakes. The general trend in cryosphere shows a significant decrease in ice storage due to warming (IPCC 2007a). Snow cover is dependent on both air temperature and precipitation. Climate change is said to be responsible for the increased summer thaw which is found to be more than the snowfall during winters. There are projections of a widespread reduction in snow cover, increase in thaw depths of permafrost region and mass loss of glaciers and ice caps (IPCC 2007a). When in equilibrium, glaciers store water during cold or wet years and release them in warmer years, thus reducing the inter-annual variability of water resources (Viviroli et al. 2011). Shrinking glaciers due to global warming might reduce their capacity to store water thus making water supply less dependable (Cisneros et al. 2014). In high altitudes, summer

**Table 7.1** Highlights of AR 4 and AR 5 with respect to climate change-induced freshwater-related risks

| **Freshwater-related risks at the global scale (AR 5)** | **Degree of uncertainty (qualitative)** |
|---|---|
| Freshwater-related risks of climate change increase significantly with increasing greenhouse gas (GHG) concentrations | *Robust evidence*, *high agreement* |
| Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions | *Robust evidence*, *high agreement* |
| Climate change is likely to increase the frequency of meteorological and agricultural drought in presently dry regions by 2100 under the RCP8.5 scenario | *Medium evidence*, *medium agreement* |
| In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected | *Robust evidence*, *high agreement* |
| Total meltwater yields from stored glacial ice in glacial-fed rivers will increase in many regions during the next decades, but decrease thereafter | *Robust evidence*, *high agreement* |
| Some GHG emission mitigation measures like bioenergy crops imply risks for freshwater systems, if they demand more water than other measures | *Medium evidence*, *high agreement* |
| **Freshwater-related risks at the global scale (AR 4)** | **Degree of uncertainty (quantitative)** |
| Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits | *High confidence* |
| Water supplies stored in glaciers and snow cover are projected to decline during the twenty-first century | *High confidence* |
| Annual average river runoff and water availability are projected to increase at high latitudes and in some wet tropical areas and decrease over some dry regions at mid-latitudes and in the dry tropics by 2050 | *High confidence* |
| Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas | *Very likely(for flooding)* <br> *Likely(for droughts)* |

Source: Bates et al. (2008) and Cisneros et al. (2014)

irrigation depends on annual snowfall, which the large glaciers and snowfields help to trap and maintain. With changing climate and receding glaciers, the summer irrigation reserves might continue to shrink (Rizvi 1998). Consequently, high-altitude agriculture, which is dependent on snowmelt and glacial water, is already facing a crisis situation (discussed in Box 7.1).

An increased melting and consequent mass loss of glaciers and ice caps worldwide and glacial retreat have also led to the formation of moraine-dammed glacial lakes. These lakes are a threat for glacial lake outburst floods particularly in the mountain ranges that are steep (e.g., the Himalayas, the Andes and the Alps) (IPCC 2007b). In the western Himalayas, there are small and stable lakes in Nepal; while Bhutan has large and numerous glacial lakes, most of which are growing and causing a continued increase in hazard (Gardelle et al. 2011). Also, the enhanced

**Table 7.2** Few examples of observed changes in freshwater resources mostly attributable to climate change

| Hydrological variable | Observed change | Region (Period) | References |
|---|---|---|---|
| Cryosphere | Decreases in the extent of permafrost | Arctic and Eurasia<br>Andes | IPCC (2013) and Rabassa (2009) |
| | Mass loss of glaciers | Global<br>Andes<br>Himalayas | Gardner et al. (2013), Rabassa 2009, Rabatel et al. 2013, and Bolch et al. 2012 |
| | Consistent decrease in snow cover | Northern Hemisphere (1966–2005) | IPCC (2007a) |
| | Decreased glacier meltwater yield | Europe (Alps) (1910–1940 vs. 1980–2000) | Collins (2008) |
| | Disappearance of Chacaltaya Glacier | Bolivia (2009) | Rosenzweig et al. (2007) |
| | Reduction of snow water equivalent | Norway | Skaugen et al. (2012) |
| | Shorter snowfall season with earlier snowmelt | Most of Northern Hemisphere | Takala et al. (2009) |
| Runoff and discharge | Changed runoff | Global (1960–1994) | Gerten et al. (2008), Piao et al.(2007), and Alkama et al. (2011) |
| | Reduced runoff | China (Yellow River) | Piao et al. (2010) |
| | Earlier annual peak discharge | The Russian Arctic (1960–2001)<br>W. USA, Columbia River (1950–1999) | Shiklomanov et al. (2007) and Hidalgo et al. (2009) |
| | Decreased dry-season discharge | Peru (the 1950s–1990s) | Baraer et al. (2012) |
| Extreme events | More intense extremes of precipitation | Northern tropics and mid-latitudes (1951–1999) | Min et al. (2011) |
| | The fraction of the risk of flooding | England and Wales (2000) | Pall et al. (2011) |
| | More severe, frequent and longer soil moisture droughts over 37% of land area | China (1950–2006) | Wang et al. (2011) |
| Groundwater | Decreased recharge of karst aquifers | Spain (20th century) | Aguilera and Murillo (2009) |
| | Decreased groundwater recharge | Kashmir, India (1985–2005)<br>Southwestern Australia | Jeelani (2008) and Government of Western Australia (2003) |

Source: Adapted from Cisneros et al. (2014)

**Box 7.1 Water-Related Adaptations for High-Altitude Agriculture**

Mountains have been referred to as the water towers of the world (Viviroli 2007). They are a major source of stored water as they contain vast reserves of water in the form of snow, ice and glaciers. Changes in temperature and precipitation are expected to seriously affect the snow and glacial melt characteristics, which are important hydrological processes in the mountains (Immerzeel et al. 2010). The water towers of Asia, the Hindu Kush Himalayas, are also known as the third pole as these are the largest areas outside the poles that are covered by glaciers and permafrost. The huge amounts of snow and ice are crucial to water, energy, food and ecological security for a large part of Asia.

Increased variation in precipitation is observed and strongly projected for the future (discussed previously in Sect. 7.2). The precipitation variation triggers floods in monsoons and scarcity in dry seasons. Thus to buffer and manage the seasonal shocks of water availability, appropriate infrastructure and institutional capacities are required in the Himalayan region (Molden et al. 2014). Water infrastructure, both physical (e.g., reservoirs, water retention ponds, etc.) and natural (e.g., watersheds, forested land, floodplains, wetlands, etc.), can moderate the variability and improve water security, agricultural productivity and adaptive capacity, if properly managed (Clements et al. 2010; Molden et al. 2014).

Among the basic approaches of adaptation to water scarcity, developing water storage facilities had been regarded as particularly relevant for the Himalayan Hindu Kush mountain regions which, despite the sufficient precipitation in most parts, face seasonal water scarcity due to intra-annual variability in precipitation, short duration of rainfall and losses due to runoff (Vaidya 2015). Water storage has been suggested as a key strategy in climate change adaptation as it can ensure water availability throughout the dry year (ICIMOD 2009; McCartney and Smakhtin 2010).

Traditional systems of water harvesting from glaciers and streams that tap glacier water are common in certain regions of the Himalayas like Chitral and Hunza districts of Pakistan and Spiti Valley of Himachal Pradesh, India; while in certain other regions in Himachal Pradesh diversion channels called *kuhls* are used to tap mountain stream for irrigation water (Agarwal and Narain 1997). The participation of the local community institutions played a fundamental role in the allocation of water and service provisions in traditional water-harvesting systems, thus also creating an appropriate "institutional environment" for making and enforcing rules (Vaidya 2015).

In Nepal, community-driven water storage structures have proven to be successful adaptation measure for seasonal water scarcity. Concrete ponds fed by streams or springs that capture excess water during periods of high flow are used to irrigate arable crops in Nepal. Low-cost plastic-lined ponds that

(continued)

**Box 7.1** (continued)

reduce seepage are an effective way to store water, particularly for vegetable crops. However, it is also necessary that water storage development with appropriate storage infrastructure be part of an integrated approach that includes improvement of land cover, soil moisture retention and facilitating aquifer recharge (Sugden et al. 2014). Often overlooked by government strategies, the approach of building decentralized small-scale and very small-scale water storage systems at a local level can ensure water availability at times of high requirement and help build community resilience to changing climate (Vaidya 2015).

In Ladakh, ice reservoir structures like artificial glaciers and ice stupas which evolved from local knowledge guided with engineering design principles have emerged as an innovative solution of water storage in the cold desert area. Ladakh is a high altitude (over 3000 m) cold desert situated in the western Himalayas, India. In the past, glaciers and snowfields have adequately supported subsistence agriculture in the Ladakh region, the sustainability of which in recent years is threatened by changing weather patterns (Mingle 2015). Unlike rain or seasonal snowmelt that reaches peak flow in a short duration, glaciers act as long-term storage units of water in the form of ice and play a central role in irrigation (Malone 2010). There is a significant reduction in water reserves in the region, which is likely to continue as the glaciers and snowfields retreat due to climate change (Grossman 2015; Mingle 2015; Rizvi 1998).

In Ladakh, winter snowfall bears a strong correlation to the amount of water available for irrigation in summer, and a low snowfall in winter indicates a summer drought (Gutschow and Mankelow 2001). Further, until seasonal glacier meltwater becomes available, typically there is a water shortage of about 2 months just before the onset of sowing due to low temperature and high variability of seasonal snow cover. Artificial glaciers are engineered ice reservoirs at lower altitudes which melt earlier and supply the necessary water for agriculture season. Artificial glacier is an intricate network of water channels and check dams that capture water for seasonal storage by freezing thin layers of water, creating superimposed sheets of ice along the upper slopes of the village valley (Fig. 7.2a, b) (Shaheen 2016; Nusser et al. 2018). These are intentional variations of traditional agriculture systems of water management like *kuhls* (channels) and zings (reservoirs located above cultivated fields) which, while retaining the conventional walls and snow barrier bands, incorporate “engineered design thinking” to manage and manipulate scarce water resource for irrigation (Clouse et al. 2017). Apart from allowing villagers to have timely and controlled access to water for irrigation water throughout the year (Vince 2010), such structures have led to a decline in water losses through

(continued)

**Box 7.1** (continued)
seepage and an extension of summer cropping season to grow cash crops like potatoes and green peas (Shaheen 2016).

Ice stupas are another recently constructed (in 2015) variation of artificial glaciers which do away with the limitation of appropriate site associated with artificial glaciers. Ice stupas use underground pipes to divert water from upper streams to preferred locations where the water is frozen as it falls through sprinkler fountainhead into a conical structure, thus holding water that would flow downstream during winters to be made available in time of spring sowing (Fig. 7.2a, b). Diversion of water, however, can create a problem in downstream areas (Shaheen 2016; Nusser et al. 2018). While artificial glaciers are site-specific and cater to previously cultivated lands, ice stupas can be constructed in barren lands, thus leading to an expansion of irrigated areas.

Climate-adaptive design interventions could become necessary to ensure agricultural stability in the face of climate change-induced diminished surface meltwater and out of season precipitation and agriculture irrigated by snowmelt (Clouse et al. 2017). Moreover, the innovative adaptation strategies (as in Ladakh) could guide similar initiatives in regions facing similar issues due to changing environmental conditions (Mingle 2009). Another noteworthy aspect of such water storage-related adaptations in high altitudes (both Nepal and Ladakh) is the community involvement in planning and maintaining such structures, besides the use of local knowledge and adaptation to community needs.

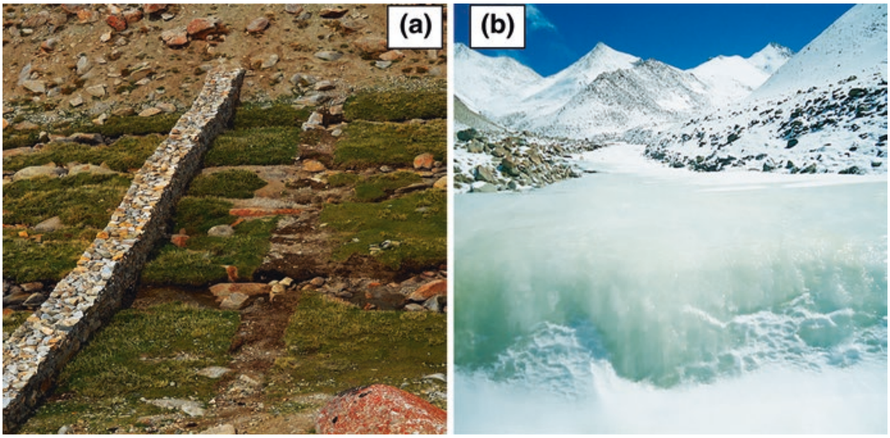


**Fig. 7.2** (**a**) Artificial glacier in summer time at Igloo, Ladakh. (Source: Clouse et al. 2017; Taylor & Francis Ltd. www.tandfonline.com). (**b**) The artificial glacier at Igloo in winter turns into a solid water reservoir. (Source: Leh Nutrition Project)

melting and increased duration of melting of glaciers led to increased river run-off and discharge peaks in shorter time frame (Jansson et al. 2003). This has been observed in the Andes and the Alps (IPCC 2007a, b).

### 7.2.2 Runoff and Streamflow

Runoff is the part of the excess water that flows over land surface under gravity instead of getting absorbed. It is caused by both natural process and human activities. Glaciers, snow and rain contribute to natural runoff. Runoff from glacier melt serves as an important water source and is occasionally the primary water source for the arid lowlands in mountainous regions. Runoff from glaciers accounts for the most important water supply source in central Asia (Chen et al. 2016). Retreat of glaciers that sustain rivers draining the glaciated regions during warm and dry periods (particularly in the high mountain ranges in Asia and the Andes) are projected to lead to intensified short-term river flows due to an increased glacier melt induced by warming, followed by a gradual fall in the longer term (IPCC 2007b). Further, the annual runoff peaks from glacierized catchments are strongly expected to shift towards spring from summers due to climate change and shrinking glaciers (Huss 2011). This has implications for downstream water flow, assuming greater significance during drought and heat waves (Koboltschnig et al. 2007).

A component of runoff which enters waterbodies is called streamflow or discharge and is expressed as the volume of water per unit time. Climate-driven changes in river flows depend largely on changes in volume, time and form (rain or snow) of precipitation and changes in evaporation (Bates et al. 2008). Changes in streamflow are also driven by non-climatic confounding factors like land use change, irrigation and urbanization (Cisneros et al. 2014). Trends in streamflow have been found to be consistent with observed trends in regional precipitation and temperature since the 1950s (Cisneros et al. 2014). At a global scale, the annual runoff increased in some regions (particularly higher latitudes in the USA) and decreased in others (parts of southern parts of Europe and South America) (Bates et al. 2008). However, the number of streamflow showing significant decreasing trends is higher than that showing a significant increasing trend in discharge in a global analysis of simulated streamflow (1948–2004) (Dai et al. 2009). Projections of runoff indicate a notable reduction in average annual runoff in dry tropical regions and southern Europe while an increase is projected for wet tropics, south-east Asia and high latitudes. "*Flows in high-latitude rivers are expected to increase, while flows from major rivers in the Middle East, Europe, and Central America might decrease*" (IPCC 2007a; Cisneros et al. 2014). In total, an increase in annual runoff is projected over the entire land surface, which in order to be fully made use of would require adequate infrastructure to capture and store the excess water (Bates et al. 2008).

Significant changes in river flows have been observed in many regions where snow falls in the winter (Bates et al. 2008). In regions with seasonal snow storage, warming has led to increased winter flows because a greater proportion of precipitation in winter falls as rain instead of snow (Clow 2010; Korhonen and Kuusisto

2010; Tan et al. 2011). Also reduced or earlier snowmelt leading to decreasing spring flows and increasing winter flows is strongly projected to alter seasonality of river flows in regions where snowfall is the predominant form of winter precipitation. Such occurrences are observed in the Himalayas, the Alps, the Scandinavian region, etc. (IPCC 2007b).

### 7.2.3 Ground Water

A decreasing trend in groundwater level of aquifers has been observed in the last few decades mostly due to groundwater abstractions (IPCC 2007b). However, the extent to which climate change is responsible for groundwater withdrawals is not known (Cisneros et al. 2014). Projected changes in groundwater levels are linked to changes in other hydrological variables due to warming. Increased groundwater abstractions and lower groundwater levels are expected due to projected increases in precipitation and streamflow variability (Taylor et al. 2013) and decreasing snowfall in sites where snowmelt provides most of the groundwater recharge (e.g., the southwestern USA) (Earman et al. 2006). With each degree rise in global mean temperatures between 0 °C and 3 °C, land areas affected by groundwater decrease are expected to increase linearly (Portmann et al. 2013). Surface water recharges and groundwater recharges are interlinked and vary with precipitation and type of soil. In humid areas, an increased precipitation variability might decrease groundwater recharge as heavy precipitation results in exceeding of infiltration capacity of the soil; while in semi-arid and arid areas intense rainfall leads to faster infiltration and, therefore, increase in recharge (IPCC 2007b).

### 7.2.4 Precipitation and Extreme Events

Precipitation varies largely in both temporal and spatial scales and is strongly influenced by “*large-scale patterns of natural variability*”. This makes it a difficult parameter to monitor trends for over a global scale and attribute changes to with certainty (IPCC 2007a). On an average, global mean precipitation trends during 1901–2005 have been found to be statistically insignificant. However, heavy precipitation events have increased extensively even where total precipitation has decreased. A notable decrease in precipitation has been observed in the tropic and sub-tropic zones (10°S to 30°N) in the past 30–40 years (Bates et al. 2008).

According to theoretical and climate model studies, increasing warming and a consequent rise in atmospheric water vapor are expected to lead to extreme precipitation events as compared to mean precipitation. Unlike extreme precipitation events that are controlled by the availability of water vapor in the atmosphere, average rainfall is influenced by the atmospheric ability to radiate long-wave energy which is, in turn, restricted by increasing greenhouse gases (GHGs) (Bates et al. 2008).

Heavy precipitation events are projected to occur more frequently with an increasing intensity at higher latitudes. Flood hazards are expected to increase over half of the world in the south and Southeast Asia, tropical Africa, northeast Eurasia and South America (Hirabayashi et al. 2013). A projected increase in precipitation intensity is also accompanied by an increase in the number of consecutive dry days in many regions due to a decrease in even spread of precipitation into concentrated intense events interspersed with longer dry periods and increased evapotranspiration, particularly, in the sub-tropical region (Bates et al. 2008). Future tropical cyclones are also more likely to get more intense with more heavy precipitation (IPCC 2007c).

Drought is another kind of extreme event that is generally classified into three types: (a) "meteorological drought" (low precipitation), (b) "hydrological drought" (low river flows and groundwater levels) and (c) "agricultural drought" (low soil moisture). Decrease in precipitation and soil moisture reduction (including diminishing snowpack in cold areas) along with increasing temperatures and the associated increase in evapotranspiration are the important factors that have contributed to the expansion of regions suffering from drought (Dai et al. 2004). Changes in sea surface temperatures also contribute to droughts in the tropics where droughts have become more common since the 1970s. Further, excessive water withdrawals can aggravate the impact of drought (IPCC 2007b). Meteorological droughts and agricultural droughts are projected to become more frequent and/or last longer in some regions and some seasons by the end of twenty-first century. There are projections of increased severity of droughts in southern Europe and the Mediterranean region, central Europe, central and southern North America, central America, northeast Brazil and southern Africa (Cisneros et al. 2014).

## 7.3 Projections of Change in Freshwater Resources and Impacts on Agriculture

Projections of freshwater-related impacts are generally evaluated by comparison to historical data. Such projections are useful in making adaptation decisions with regard to climate change (Cisneros et al. 2014). Projections also help to quantify the likely outcomes under current management practices apart from indicating the necessary actions to avoid unfavourable outcomes in future (Oki and Kanae 2006). Projections are based on different scenarios simulated using different climate models, the outcome to which might vary widely. Scenarios represent possible future emission pathways and are used as a basis for exploring a realistic set of future projections of climate change. Previously IPCC assessments used a set of scenarios (A1, A2, B1 and B2 family) called SRES (Special Report on Emissions Scenarios) which were driven by a range of factors like demographic development, socio-economic development and technological change. Scenario A1 assumed a globalized future with rapid economic and technological growth. A2 scenario assumes more regional emphasis while scenarios B1 and B2 assumed more sustainable practices with a global and regional focus, respectively (IPCC 2000). SRES was replaced by RCP (representative concentration pathways (RCPs) in the IPCC fifth assessment report (AR 5) which takes into account climate change mitigation policies to limit emissions. The four RCP scenarios (RCP 2.6, RCP4.5, RCP6, RCP8.5) are named after the approximate radiative forcing values (2.6 W/m$^2$, 4.5 W/m$^2$, 6.0 W/m$^2$, 8.5 W/m$^2$, respectively) in year 2100 relative to the pre-industrial values. Radiative forcing or climate forcing is the difference between solar irradiation absorbed by the Earth and energy radiated back to space. A positive radiative forcing indicates a net gain in energy and causes warming. As of 2016, the radiative forcing was 3.027 W/m$^2$. The RCP2.6 scenario is the lowest emission range pathway and requires robust mitigation of GHG concentrations in the twenty-first century. The RCP4.5 and RCP6.0 scenarios are medium emission range scenarios. While the RCP8.5 scenario is a high range emission scenario with no mitigation, it is closest to a 'business as usual' scenario of fossil fuel use (Mann and Gaudet 2018). Few projections of future changes in freshwater resources under different climate scenarios are presented in Table 7.3.

A general trend in projections of water resources due to global warming in the future indicate decreased renewable water resources (Portmann et al. 2013; Schewe et al. 2014), aggravated water scarcity (Gerten et al. 2013) and increased exposure to floods (Hirabayashi et al. 2013). Precipitation events are expected to be more variable and more intense with increased frequency of extreme events like floods and droughts. Higher temperatures and higher variability in precipitations will lead to an increase in irrigation water demand irrespective of total precipitation in the growing season (IPCC 2007b). The increased variability of river flow, due to variability in precipitation and decreased snow and ice storage, is expected to decrease reliable surface water supply in the future. This would further complicate the situation in areas where the groundwater levels are projected to decline, as well as groundwater resources cannot be used to ease stress caused by freshwater unavailability (Kundzewicz and Döll 2009). Overall by 2050, under A2 and B2 scenarios of SRES, water stress is projected to increase over 62–76% of the area globally, primarily due to increased water withdrawals and decrease in 20–29% area due to increased precipitation (IPCC 2007b). Another study projected a 10- to 30-fold increase in the proportion of land facing extreme drought and a 2-fold and 6-fold increase in the frequency of 'extreme drought events' and 'mean drought duration', respectively, for A2 scenario by 2090 (Burke et al. 2006). However, a change in population is anticipated to have a greater impact on water availability and water demand than climate change in the future (Cisneros et al. 2014; Gerten et al. 2011).

Climate change can threaten water security by altering the availability of water. Crops depend on a balance between soil water moisture and atmospheric moisture deficit apart from crop management practices. Future crop water demand would be affected by variations in precipitation, and changes in radiation and temperature in both irrigated and rainfed systems (Cisneros et al. 2014). However, rainfed agriculture, which accounts for 80% of the total cultivated land area, is more vulnerable to variability in precipitation (projected to affect yields) (Finger et al. 2011). In areas where rainfall is projected to increase in the monsoon season, less irrigation may be required for paddy rice cultivation (Yoo et al. 2013). Irrigation, on the other hand, accounts for 70% of global water withdrawals and greater than 90% of consumptive water use (IPCC 2007b). Without considering climate change effects, the FAO

**Table 7.3** Projected hydrological changes under different climate change scenarios

| Projected hydrological change | Region/scale | Change in different emission scenarios/degrees of global warming | References |
|---|---|---|---|
| The decrease of renewable water resource by more than 20% | Global | – | Schewe et al. (2014) |
| The decrease of more than 10% in groundwater resource by the 2080s as compared to the the 1980s | Global | – | Portmann et al. (2013) |
| Increase in irrigation water demand | Global | Mean change of required irrigation water withdrawals by the 2080s as compared to the 1980s | Hanasaki et al. (2013) |
| | | RCP2.6: −0.2 to 1.6% | |
| | | RCP4.5: 1.9–2.8% | |
| | | RCP8.5: 6.7–10.0% | |
| Shifts in river flow regime from perennial to intermittent and vice-versa | Global | Percent of the global land area affected by regime shifts between the 1970s and the 2050s | Döll and Müller Schmied (2012) |
| | | SRES B2: 5.4–6.7% | |
| | | SRES A2: 6.3–7.0% | |
| Decrease in groundwater recharge | Australia | Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050: GW 1.4°C: Close to 0 almost everywhere GW 2.8°C: In western Australia 0.2–0.6, in central Australia 0.2–0.3, elsewhere close to 1 | Crosbie et al. (2013) Holman et al. (2009) |
| | East Anglia, UK | Percent change between baseline and future (by 2050s) groundwater recharge | |
| | | SRES B1: −22% | |
| | | SRES A1f: −26% | |
| Increase in agricultural (soil moisture) droughts | France | Smaller increase for SRES B1 as comapred to A2 and A1B | Vidal et al. (2012) |
| 9–17% reduction in the annual mean snow coverage by 2100. | Northern Hemisphere | B2 scenario | IPCC (2007a) |
| 20–35% likely decrease in permafrost area by 2050 | Northern Hemisphere | – | IPCC (2007b) |

Source: Adapted from Cisneros et al. (2014)

projected a likely expansion of irrigated area by 0.6% per year till 2030 in the developing countries (water-stressed areas including southern Asia, northern China, northern Africa, etc.) and a cropping intensity increase from 1.27 to 1.41 crops per year with slight increase in irrigation water use efficiency (Bruinsma 2003). Under climate change, future irrigation water demand is projected to surpass water availability in various regions (Wada et al. 2013). Irrigation water demand is projected to increase significantly in Europe, USA and parts of Asia. Different models using different scenarios have projected varying levels of changes in irrigation water demand (Cisneros et al. 2014). The reversal of 20–60 million hectares of irrigated cropland to rainfed management by 2100 due to freshwater limitations is projected in some irrigated regions (western USA; China; and West, South and Central Asia) while in other parts (northern/eastern USA, parts of South America, Europe and South East Asia) increase in water supply is expected to increase net irrigation, provided substantial investments are made in irrigation infrastructure (Elliott et al. 2011).

## 7.4 Adaptation Options in Agriculture

Adaptation, in general, means the process of changing to suit a new situation. With respect to climate change, adaptation is defined by Burton (1996) as "all those responses to climate change that may be used to reduce vulnerability or to actions designed to take advantage of new opportunities that may arise as a result of climate change". It can involve both building adaptive capacity and implementing adaption decisions. Building adaptive capacity implicates increasing the ability of individuals, groups or organizations to adapt to changes while implementing decisions transform capacity into action (Adger et al. 2005). Adaptation has been recognized as a response measure to address the impacts of climate change and reduce vulnerability. Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to promote and facilitate adaptation to address climate change (UNFCCC 1992, 1998).

Several studies have classified adaptation measures differently. However, with regard to agri-water sector, autonomous adaptation options are particularly important as well as widespread (Iglesias and Garrote 2015; Bates et al. 2008). Autonomous adjustments are independently developed and implemented mostly short-term adjustments that result from changes to meet "*altered demands, objectives, and expectations*" and are "*not a conscious response*" to cope with climate change (Bates et al. 2008). Farmers have traditionally and naturally taken action in response to changes; this is in contrast to policy-driven or planned adaptation where the action is taken after policy level decision (Stern 2006).

This section discusses some of the important and frequently implemented adaptation measures in the agriculture sector that address water scarcity issue. An important element of water scarcity responses in relation to the agriculture sector is to ensure that water demand is managed at a sustainable level given local supply and availability (Anderson et al. 2008). On the other hand, the adaptation measures related to floods usually include infrastructural reforms of surface storage (dams,

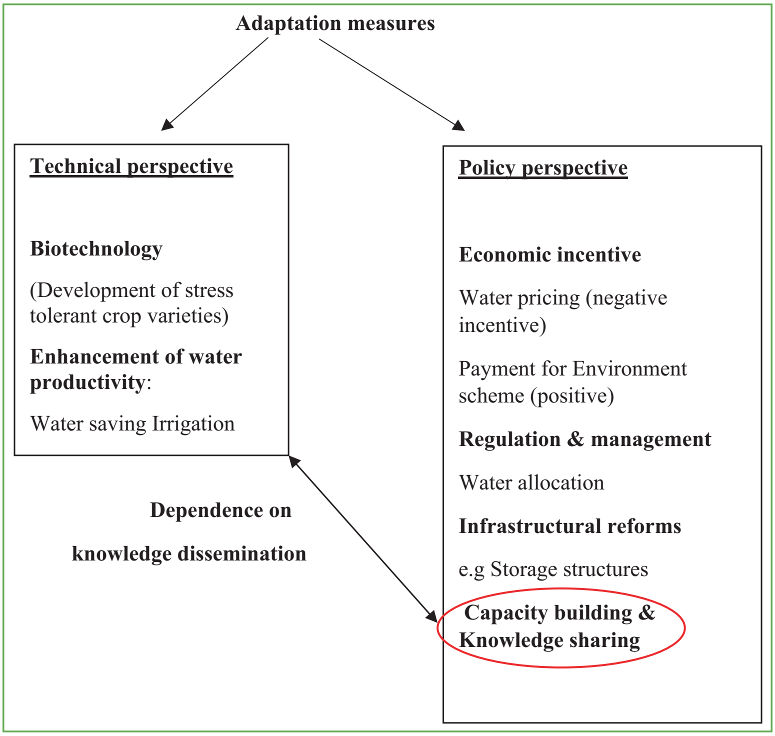


**Fig. 7.1** Adaptation measures. (Source: Adapted from Gil and Kamanda 2015; Levidow et al. 2014)

reservoirs) and prevention of flows through embankments and dykes. However, specific "concrete" actions solely in response to climate change are very rare as climate change is one of the many factors affecting investment plans and strategies, and there is some degree of uncertainty associated with projections of future hydrological changes (Bates et al. 2008). The adaptation measures in the water sector can be broadly classified into technical and policy perspectives (Fig. 7.1).

### 7.4.1 Technical Perspective

Global studies on potential impacts of climate change indicate a reduction in water availability for irrigation purposes across all regions (Iglesias and Garrote 2015). Projected future water scarcity alongside an escalating water demand with an ever-increasing population and expansion of irrigated farming necessitates sustainable management of present water resources. Presently, irrigation efficiency is very low with only 55% crop water usage (Chartzoulakis and Bertaki 2015). Improving irrigation water productivity involves the reduction of water loss in the crop production system while maintaining crop yield at a certain level (Kang et al. 2017).

Climate-smart agricultural technologies (Venkatramanan and Shah 2019) and advanced irrigation technology like water-saving irrigation (WSI) and deficit irrigation techniques can promote sustainable use of limited water resource and minimise the impact of water scarcity (Chartzoulakis and Bertaki 2015). However, adaptation as a whole and adoption of sustainable measures are local processes, which apart from technology are also dependent upon factors like socio-economic conditions, and legal and institutional frameworks (Chartzoulakis and Bertaki 2015).

#### 7.4.1.1 Water-Saving Irrigation

Water-saving irrigation has been noted to play a positive role in coping with the impact of climate change. For instance, in China the implemented WSI techniques are expected to save 30 billion cubic meter water per year (Zou et al. 2012). Few widely implemented water-saving irrigation techniques to address the impacts of climate change have been discussed.

Localized irrigation (drip/trickle, micro-sprayers) is a widely recognized efficient means of irrigating individual plants using pipes laid on the ground surface (Chartzoulakis and Bertaki 2015). Drip irrigation comprises of frequent (usually every 1–3 days) application of water close to plant roots through a system of small diameter plastic pipes with outlets called emitters or drippers at very low rates (2–20 l/h). Sprinkler irrigation involves the spraying of water pumped through a pipe system using rotating sprinkler heads. In canal-lining irrigation, the addition of an impermeable layer to the bed and sides of the canal significantly reduces water losses in a canal through seepage and water consumption by weeds. Low-pressure irrigation uses a pressurized piped system and uses pressure (2–3 bars) to convey and distribute the irrigation water from source to the irrigable area in closed pipes. Small flow rates cover large areas regardless of slope and topography. The quantity of water saved per acre can be determined by the water-saving rate. Table 7.4 provides a summary of water-saving rates for WSI techniques (Zou et al. 2012).

The high installation cost remains a major barrier to the expansion of the use of micro-irrigation techniques which represent only 6% of the total irrigated area despite a 50-fold increase in the last 20 years (Chartzoulakis and Bertaki 2015). On the other hand, propagation of use of drip irrigation by government subsidies has not borne the desired results in some cases. Government subsidies in drip irrigation in Madhya Pradesh, India, have had negative consequences and hindered access to the technology to smallholder farmers because of "*technical requirements, highly bureaucratic process*" and agents emerging as middlemen, thus increasing prices up to 40% (Malik et al. 2016).

**Table 7.4** Summary of water-saving rates for WSI techniques

| Technique | Range(%) | Average(%) |
|---|---|---|
| Micro-irrigation | 35–70 | 52.7 |
| Sprinkler irrigation | 30–65 | 45.3 |
| Low-pressure irrigation | 20–38 | 29.4 |
| Canal lining | 16.2–36.2 | 24.5 |

In a study on the economic feasibility of water-saving irrigation (WSI) techniques in China, micro-irrigation (including drip irrigation, mini-sprinkler irrigation and bubbler irrigation) was found to be the most effective measure, in terms of both adaptation and mitigation to climate change. Mitigation here means lesser energy consumption and reduction in GHG emissions. Using micro-irrigation techniques led to the least amount of $CO_2$ eq. emissions per unit cubic meter of water saved as well as per kilogram increase in grain yield among the other WSI. From an economic perspective, canal-lining irrigation, which involves adding an impermeable layer, was found to be the least cost option in the long term due to energy and water cost savings. While sprinkler irrigation and low-pressure pipe irrigation have a larger potential for water saving and increasing grain yield, these techniques also incur additional energy needs to attain a certain water pressure, therefore, leading to higher GHG emissions. Hence considering both adaptation and mitigation, they were the least preferred (Zou et al. 2013).

#### 7.4.1.2 Deficit Irrigation

Unlike the water-saving irrigation technique which leads to water saving through prevention of loss but meets full crop water requirements, deficit irrigation techniques maximize water use efficiency by meeting partial crop water requirements. Techniques like regular deficit irrigation (RDI) and alternate partial root drying and subsurface drip irrigation are optimizing strategies mostly used in arid and semi-arid regions for more effective use of limited water resources. Since the yield is directly proportional to crop water consumption (Perry et al. 2017), deficit irrigation techniques have a trade-off of slightly reduced yield as compared to WSI production. However, deficit irrigation prevents the reduction in irrigated area. Thus crops which are less sensitive to water stress can adapt well to various deficit irrigation practices. As water can be applied precisely to individual plants, RDI and alternate partial root zone irrigation (APRI) strategies are suitable for fruit trees. For cereal crops like maize, wheat and sorghum, research is ongoing and is required with regard to "*the timing of RDI and the degree of soil water deficit and the timing and method of APRI in different climates, cereal varieties and planting conditions*" (Kang et al. 2017).

In regular deficit irrigation (RDI), plants are exposed to a regulated level of water stress during particular stages of growth in order to control excessive vegetative growth, and irrigation is applied in the whole root zone (Goodwin and Jerie 1992; Boland et al. 1993). Introduced in the 1970s for pome and stone fruit orchards, it has been successfully used for field crops, fruit trees, and greenhouse vegetables, grape, apple, jujube, maize, sorghum, wheat, potato, cotton, etc. (Kang et al. 2017). High-yielding varieties are more sensitive to water stress and, therefore, not suitable to RDI. Crops or varieties with a short-growing season are more suitable for RDI (Chartzoulakis and Bertaki 2015).

Alternate partial root zone irrigation (APRI) makes use of alternate irrigations usually in a 7–14 day cycle in different parts of root zone such that one half of the root system remains dry while the other half is irrigated. A balance between vegetative and reproductive growth is achieved by induction of a biochemical response from plants primarily through abscisic acid (ABA) hormone, which leads to reduced transpiration by partial stomatal closure and improves water use efficiency (Loveys et al. 1999). It has been used in sugar beet, sugarcane, winter wheat, sorghum, maize, cotton, potato, tomato, beans, apple, grapes, pear, etc. (Sepaskhah and Ahmadi 2010). Even though the implementation cost of alternate partial root zone drying irrigation (APRD) is high, it is economical in places where the price of water is higher in terms of availability or irrigation cost (Chartzoulakis and Bertaki 2015).

The use of RDI necessitates implied knowledge on a number of parameters including crop response to water deficits, identification of critical crop growth stages, water retention capacity of soil, economic impact of yield reduction and most importantly a certain degree of technological development to assess crop water requirement in order to support an optimum irrigation water scheduling. To that end, the use of models like FAO CROPWAT has been proven to be very useful in predicting and disseminating practical recommendations on deficit irrigation scheduling under various conditions of water supply, soil and crop management (Smith and Kivumbi 2000). Such pre-requisite knowledge relies on an effective and continuous effort on capacity building and communication between extension workers and farmers.

Subsurface irrigation is a low-pressure highly efficient irrigation system that uses buried pipes to deliver water thus minimizing losses due to evaporation and incidences of weed and diseases. Subsurface irrigation is suitable for nearly all crops, particularly for high-value fruit and vegetables. High initial investment and the possibility of clogging due to poor water quality are the major disadvantages (Chartzoulakis and Bertaki 2015).

#### 7.4.1.3 Agricultural Practices

Both properly managed irrigation technology and better agricultural practices determine greater water use efficiency (Levidow et al. 2014). Apart from irrigation management, good agriculture practices based on farm-level decisions for reducing exposure to climate risks have been recognized and recommended for achieving greater synergies (Molden et al. 2010). Such practices include retention of soil moisture and increasing the infiltration of rainwater into the soil through conservation tillage and mulching, soil surface tillage, bed surface profiling and increasing the amount of organic matter; diversification of crop types/change in timing and change in cropping patterns through a switch to crop types and varieties which use lesser water (e.g., varieties tolerant to abiotic and biotic stress); and decreasing runoff, retaining moisture and improving water uptake by changing land topography through contouring and terracing and building small-scale storage structures and recharge areas to capture rainwater (Smit and Skinner 2002; Anderson et al. 2008; Chartzoulakis and Bertaki 2015). The concept of water footprint as a tool to make decisions on cropping patterns has been discussed in Box 7.2.

**Box 7.2 Water Footprint as a Tool to Optimize Cropping Patterns**

The importance of change in cropping patterns as an adaptation measure noted by several studies is summarized by Levidow et al. (2014) as "If agricultural water demand is inelastic, then policies which encourage changes in cropping patterns can be more effective than higher prices." Water footprinting can be used as a tool to optimize cropping patterns. The water footprint is an indicator of direct and indirect freshwater consumption of a consumer or product. The water footprint of a product is the volume of freshwater used to produce that product over the entire supply chain. It is a comprehensive indicator of freshwater appropriation which is spatially and temporally explicit. The volumetric water footprint comprises three components: *blue water footprint* refers to water consumed (lost water that does not immediately return to the same water body/catchment) from surface and groundwater sources; *green water footprint* refers to consumption of rainwater while *grey water footprint* is an indicator of the volume of water polluted, i.e., the freshwater volume required to assimilate the pollutant load to bring it to natural conditions/ambient standards (Hoekstra et al. 2011). The volume of blue water used depends on the crop type, crop tolerance to water deficits, irrigation efficiency and on green water. Blue water is used whenever green water is insufficient to meet the crop water requirement (Lovarelli et al. 2016). Green water particularly refers to the rainfall evaporated from the soil, absorbed and transpired by the crop, and the water incorporated in the harvested crop (Hoekstra et al. 2011). The total water footprint (WF) of the process of growing a crop is equal to the sum of all three components, i.e., green, blue and grey. The WF is commonly expressed as the water volume used to produce a unit of product ($m^3$/tonne), the blue and green components of which are calculated by calculating the accumulation of evapotranspiration of rainwater and irrigation water, respectively, over the complete growing period divided by the yield.

Crop evapotranspiration (ET) is defined as the combination of separate processes of water evaporation from the soil surface and transpiration from the crop (Allen et al. 1998). It can be measured directly in the field or estimated based on models. FAO CROPWAT is one of the most commonly used models for estimating crop ET based on climate data of a place. Irrigation schedules for deficit irrigation practices are based on crop evapotranspiration rates. Evapotranspiration rates depend on soil and weather parameters like sunshine hours, radiation, wind speed, precipitation and temperature which vary from place to place resulting in a large variation in water footprint irrespective of crop variety. Hence, for a particular crop, blue WF might be higher in some areas and lower in others, within the same basin or region. Allocation of crops from high to low WF can result in significant savings in surface and groundwater resources (Mali et al. 2018). Optimizing cropping patterns is a key to sustainable water use in areas facing water crisis (Zeng et al. 2012).

(continued)

**Box 7.2** (continued)

Evaluation of regional water footprint to influence decisions on cropping pattern can lead to considerable water saving. A study on assessments of water footprint in the Gomti river basin of the Indo-Gangetic plains, India, found that under the present cropping pattern, a considerable part of blue water was used to grow low-value crops like chickpea, mustard and pearl millet, which can yield well even under rainfed conditions, and confining such crops to rainfed areas would lead to savings in blue water. Reallocation of cropping patterns through policy reforms that limit farmers' choice of crops and areas to minimize blue water use within a water scarce basin; and improving the efficiency of rainwater use, can potentially reduce blue water use in the basins (Mali et al. 2018). Cropping patterns that focus on high-value low water-intensive crops rather than higher net returns per unit area contribute to higher economic water productivity (Mali et al. 2018). This is particularly relevant in water-scarce places where water allocation and water pricing practices are implemented.

As a part of the integrative approach (discussed in Sect. 7.4.2.3), successful reduction in irrigation water use while maintaining farmer's income was achieved in the Shiyang river basin, China, by changing cropping patterns. Replacement of cereal crops (spring wheat and maize) by cash crops (grape and cotton) led to lesser water consumption as grapevine and cotton (350 and 320 mm, respectively) have lesser evapotranspiration rates compared to wheat and maize (450 and 500 mm, respectively). However, economic sustainability of farmers is a criterion to consider while planning a switch in cropping patterns (Kang et al. 2017).

Another approach of water footprinting is the stress weighed water footprint which measures the impact of water consumption on regional water stress by multiplying the volume of blue water with water stress index (WSI). It takes into account only blue water as green water does not contribute to water scarcity (Ridoutt and Pfister 2010). WSI is a sustainability indicator, defined as the relationship between water use and availability. Stress-weighted WF could be used to quantitatively compare production systems/products in terms of their contribution to water scarcity. Considering the spatial variability in stress-weighted WF, allocation of water-intensive crops to regions having lower stress-weighted WF would reduce pressure on blue water. Thus, both volumetric WF and stress-weighted WF can be used to make decisions on ways to increase crop water productivity and reduce water stress from a national perspective (Wang et al. 2015).

Further, it is shown that international trade via virtual water trade of agriculture products, i.e., export of a product from water-efficient region (relatively low virtual water content of the product) to water-inefficient region

(continued)

**Box 7.2** (continued)
(relatively high virtual water content of the product) saves water globally (Chapagain et al. 2006). Closely linked with water footprint concept, the virtual water content is the volume of water embedded in a food or other products. The redistribution of food trade has been considered as a potential climate change adaptation measure (Nelson et al. 2009). Staple food trade-related water savings are projected to increase under climate change particularly for wheat trade where large volumes of wheat would be traded from relatively water-efficient exporters to less-efficient importers (Konar et al. 2013). However, optimization of global water resources through enhanced virtual water trade while relieving pressure on water-scarce regions might also create additional pressure on export-oriented countries that produce the water-intensive commodities (Chapagain et al. 2006).

### 7.4.2 Policy Perspectives

#### 7.4.2.1 Jevon's Paradox

There is a postulation in economics called Jevon's paradox or rebound effect which states that a technological progress that enhances the efficiency of use of a natural resource tends to lead to an increase in its consumption due to an increase in demand. Lately, Jevon's paradox has been discussed and observed with regard to agricultural water use and irrigation technologies that have improved water use efficiency. The very few studies on the impact of the use of irrigation technology indicate that technologies that improve irrigation efficiency lead to increased consumptive water use and groundwater extractions (Grafton et al. 2018; Perry et al. 2017; Pfeiffer and Lin Lawell 2014). This is because the "saved" water, which results from the efficient use of water, is diverted to gain higher production (since yields increase with a marginal increase in water supply), increasing acreage or changing cropping patterns to more water-intensive (and probably income-generating) crops, thus leading to an increase in on-farm water consumption and groundwater extraction (Perry et al. 2017; Pfeiffer and Lin Lawell 2014). Increase in the irrigated area leads to increased crop transpiration and reduced percolation for aquifer recharge or downstream flows, thus increasing local water consumption (Perry et al. 2009).

Subsidies in technologies that promote irrigation efficiency have also led to decreased groundwater levels in several cases. Subsidies to drip irrigation have been found to increase water extractions due to increase in irrigated area in New Mexico (Ward and Pulid 2008) and Rajasthan, India (Birkenholtz 2017), where the volume of water applied also increased. Reduced recoverable return flows to aquifers and overexploitation of groundwater and aquifer due to cropping intensification after the adoption of drip irrigation in Souss and Tensift basins, Morocco, has been reported (Molle and Tanouti 2017). In Snake River, Idaho, USA, growth in irrigation efficiency has led to reduced groundwater recharge and drop in the Eastern Snake Plain

Aquifer level by 30% since the mid-1970s (McVeigh and Wyllie 2018). Like these cases, irrigation-efficient technologies in general, like drip irrigation, are applied in arid and semi-arid areas already facing acute water scarcity. Increased water withdrawal due to the expansion of irrigated area or increase in water consumption per unit area exacerbates the water scarcity problem. Therefore, water allocation/regulated access to water has been strongly suggested as a measure for decreasing water consumption and recommended as a crucial step to be taken prior the introduction of hi-tech irrigation (Perry et al. 2017). Introduction of water-efficient irrigation technology is not an isolated process as remarked by Grafton et al. (2018) that:

"Increases in irrigation efficiency must be accompanied by robust water accounting and measurements, a cap on extractions, an assessment of uncertainties, the valuation of trade-offs, and a better understanding of the incentives and behavior of irrigators."

#### 7.4.2.2 Water Pricing and Water Allocation

The price of water is generally low, and correct water pricing is essential for water pricing to be an effective measure (Perry et al. 2009). There are few positive references on water pricing policy. Higher irrigation water prices have encouraged farmers in Europe to adopt IS-DSS (irrigation scheduling decision support system) (discussed in Sect. 7.4.2.4) (Giannakis et al. 2016). Volumetric water metering and water accounting procedures have been recommended for proper water pricing (Chartzoulakis and Bertaki 2015). A study of farmer's responses to changes in water pricing practices indicated that solely increasing water prices is not a viable option and an integrated approach is necessary (Mamitimin et al. 2015). The efficiency of water pricing mechanisms is further hampered by low water price elasticity, large differences in prices within and outside country and political issues related to enforcement (Giannakis et al. 2016). Largely, the economic instrument of water pricing to reduce water demand has been found to be ineffective (Molle and Berkoff 2007; Molle 2008). Also, crop-specific differences in irrigation efficiency are not accounted for in this measure, causing a heavy penalty for certain crop growers like rice, and in a few cases it has led to abusive water utilization by the wealthier stakeholders (Gil and Kamanda 2015); besides farmers view it as an extra penalty (Molden et al. 2010).

Water allocation measures, on the other hand, are more effective in protecting available water resources (Gil and Kamanda 2015), leading farmers to adopt water-efficient practices (Molden et al. 2010). It is one of the key adaptation measures to tackle water scarcity (Iglesias and Garrote 2015), and a crucial supplement to irrigation technologies (Perry et al. 2017; Grafton et al. 2018). Even though quotas can be subject to arbitrariness and adapt to changing economic conditions; they were found to be consistently preferred over economic regulations, as they were more equitable, transparent and efficient in aligning demand and supply with limited overall income loss as compared to price-based regulation (Molle 2008). However, practically determining a "socially optimal distribution" for water allocation is difficult, as is meeting the high costs associated with the assignment, administration and monitoring (Gil and Kamanda 2015). Because the potential solutions to allocation problems like changes in infrastructure, land use or limitations of irrigation could lead to conflict among stakeholders, this necessitates the incorporation of interests of different stakeholders while decision-making (Iglesias and Garrote 2015). Additionally, the sustainable threshold of water demanded by each region needs to identified and considered in decisions related to the distribution of regional water resources in different sectors (Kang et al. 2017).

#### 7.4.2.3 Integrated Measures

Integrated measures combining multiple approaches have been successfully implemented in the arid inland area of Shiyang River Basin, China, in order to address water scarcity and improve overall water productivity. The approach included a combination of measures like closing over 3000 wells, reducing planting and irrigation area through changing cropping patterns and building solar greenhouses for high value crops, adjusting planting systems, "developing comprehensive water-saving technologies and their integrated models such as adopting deficit irrigation, drip irrigation under mulch, field levelling, etc., implementing water right management through strict irrigation quota and step-price system", and demonstrations and farmers' trainings and workshops on water-saving technologies, water resources management and water-saving in agriculture. These measures worked synergistically to not only improve irrigation efficiency, water productivity and groundwater levels but also maintained farmers' income (Kang et al. 2017).

#### 7.4.2.4 Capacity Building

Compared to measures that place obligations and forceful implementations for water saving, positive incentives which provide compensations and tax exemptions for adopters of water management like the payment for environment services schemes (PES) are becoming popular particularly in Latin America (Gil and Kamanda 2015).

A bottleneck over the use of technical advice on irrigation schedule is the lack of adequate assistance and knowledge gap between farmers' actual practice and potential crop water use (Levidow et al. 2014). Irrigation scheduling decision support systems (IS-DSS) is a computer-based tool which provides advice to farmers on real-time irrigation scheduling and ensures water-efficient agriculture. It has been largely applied in southern parts of Europe and Italy (Mannini et al. 2013). However, not all technologies are equally widely adopted in all regions and the reasons also help to identify bottlenecks. For instance, despite the large potential for water saving by the use of IS-DSS in the Mediterranean region, it was not widely adopted due to lack of proper dissemination and the actual transfer of knowledge in the field. This highlights the need for technology to be user-friendly and the importance of a participatory approach which encompasses the stakeholder's perspective in the technology design or implementation (Giannakis et al. 2016).

A farmer's general perspective on improving water efficiency is on revenue maximization rather than water saving (Knox et al. 2012). Even while policymakers and water managers limit allocation of water as part of reducing water use, water saving is not a priority for farmers (Luquet et al. 2005). The farmer exhibits a tendency to avert risks and wants to derive the maximum of the limited resource, in this case water available to him, by consuming as much as possible. This is also the reason why subsidies and technology have not worked in the intended ways as discussed previously.

Analysis of farmers' adaptation to water scarcity in Al-Bayda canal in Nile Delta, Egypt, revealed there are a number of factors beyond water scarcity and profit maximization that shape the response of farmers' which include collective dimension of individual crop choice, farm fragmentation, risk aversion, social capital and history of farmers (Ghazouani et al. 2014). The way farmers react to a change in policy also depend on a number of factors, for instance, a study on change in water pricing in Tarim Basin, China, found that small farmers and farmers growing perennial fruit trees tend to opt for drill wells when water prices increased while large farmers and farmers with annual crop production opted for options other than drill wells (like adopting improved irrigation technology, improved crop production or do nothing). Further, it was found that farmers who suffered slight water shortages in the past were more likely to use water more wisely (Mamitimin et al. 2015). The behaviour of irrigators is an important factor that should be taken into account while implementing policies (Grafton et al. 2018). The significance of understanding stakeholder's perception on climate change and adaptation policies and their participation in decision-making have been highlighted by several studies (Iglesias and Garrote 2015; Gil and Kamanda 2015; Kang et al. 2017; Giannakis et al. 2016; Levidow et al. 2014).

In a study by Levidow et al. (2014), it has been demonstrated that farmers in spite of making investments in irrigation technologies cannot reap the full benefits because of "*inadequate knowledge regarding crops' water use, soil-moisture conditions, irrigation scheduling techniques, crops' yield response to different irrigation management strategies, etc.*" While farmers have a responsibility for increasing water use efficiency, it is getting displaced due to lack of knowledge exchange systems that can identify scope for improvements and uphold the shared responsibility of relevant stakeholders across the entire water supply chain. Only a greater institutional responsibility for water policies and strategies can support an adequate knowledge system (Levidow et al. 2014). Adopting optimized and integrated technologies requires cooperation from different agencies like scientists, technicians, local agencies, financial incentives and farmers themselves (Kang et al. 2017), including a stronger extension service (Mamitimin et al. 2015).

## 7.5 Conclusion

There are evidences that climate change is associated with changes in the hydrological cycle. Freshwater resources are already vulnerable to climate change and have the potential to be strongly influenced by it in the future. Future projections in general indicate a reduction in water availability at the global scale and risk of frequent extreme events. This would have a huge impact on the agriculture sector which relies heavily on water. The situation is further complicated by confounding non-climatic drivers like population growth which would continue to increase the demand for freshwater and put tremendous pressure on available water resources. In this context, adaptation can increase preparedness to face the uncertainties posed by climate change and reduce vulnerability. The adaptation measures in agriculture to address freshwater scarcity have been discussed. In high altitude mountains, the observed effects of climate change on water resources are profoundly impacting agriculture. Communal water harvesting through storage structures is the primary means of adaptation in high altitudes. Innovative adaption measures in Ladakh which amalgamate local knowledge, community participation and technical expertise are particularly noteworthy; such measures can guide similar initiatives in other regions. It is important that adaptation measures should be evaluated for their long-term feasibility and effect on water scarcity. A rebound effect/Jevon's paradox has been observed in places where increases in irrigation efficiency were achieved. Policymakers have to be cautious of such effects before promoting and subsiding efficient irrigation technology; integrating it with other measures like water allocation has been strongly recommended. Integrated approaches work synergistically and, therefore, can be much more effective than measures implemented in isolation. Technology interventions also necessitate knowledge sharing and capacity building so that it remains effective. Lastly, adaptation is a local process, and every region should actively involve the stakeholders in decision-making to develop an appropriate adaptation strategy that is in harmony with its institutional and socio-economic capacities and geographic limitations.

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