Climate-smart water technologies for sustainable agriculture: a review

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ABSTRACT

Worldwide water management in irrigated and rain-fed agriculture is becoming more and more complex to overcome the expected water scarcity stress. In addition to this, challenges of global warming and climate change would have to be met through the judicious application of water in agriculture through climate-smart water technologies. Agriculture is an important sector in India and many developing countries, providing huge employment opportunities to rural populations, and supporting them to achieve food and nutritional security goals. In this paper, an attempt has been made to address challenges of increasing food production and improving rural livelihoods, while safeguarding critical water resources for sustainable use through adaptive measures for effective water management, particularly in drought-prone regions. An integrated approach needs to be implemented in agricultural water management through adoption of innovations such as water harvesting, micro-irrigation and resource conservation farming to increase water-use efficiency in agriculture and other critical services to humans and animals. The aim of this study is to facilitate an improved understanding of the potential implications of climate change and adaptation options for agricultural water management and thereby assist policymakers in taking up adaptation challenges and developing measures to reduce the vulnerability of the farming sector to climate change.

Key words | adaptation and mitigation, climate change, climate-smart water technologies, water saving technologies, water use efficiency

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INTRODUCTION

In the 21st century, climate change has emerged as a significant challenge to agriculture, freshwater resources and the food security of billions of people in the world (Goyal & Rao 2018). Studies on the impact of climate change have shown clear evidence for an observed change in global surface temperature, rainfall, evaporation and extreme events (Altieri & Nicholls 2017). The Fifth Assessment Report of the International Panel on Climate Change (IPCC) has reported on climate change and its observed consequences in South Asia (IPCC 2014). Findings of several studies also indicated that crop production could be significantly impacted due to temporal and spatial variation in the rainfall pattern, increase in temperature and variations in frequency and intensity of extreme climatic events such as floods and droughts (Aggarwal *et al.* 2009; Lobell *et al.* 2012; Brida & Owiyo 2013; Prasanna 2014; Malhotra 2017). The effect of variation in rainfall patterns may affect the natural recharge process, and increased temperatures may enhance crop evapotranspiration and irrigation demand in a different part of the world (Patle *et al.* 2017). An analysis of ensemble probabilistic scenarios for India derived from more than 50 CMIP5-GCMs data for 2020, 2050 and 2080 indicated that the rise in minimum temperatures is projected to be more than the increase in maximum temperatures, whereas a rise in temperatures would be greater during Rabi season than during Kharif season (NICRA 2016).

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Rain-fed agriculture will be primarily impacted due to rainfall variability and reduction in the number of rainy days (Venkateswarlu & Shanker 2012). Declining net productivity of horticultural crops is likely to be caused by a short growing period, terminal heat stress, soil moisture stress and decreased water availability (Aggarwal *et al.* 2009). India has a net cultivated area of 142 million hectares (Mha), out of which, about 54% is rain-fed (Sikka *et al.* 2016). The estimated impacts of climate change on cereal crop yields in different regions of India indicate that the yield loss could be up to −35% for rice, −20% for wheat, −50% for sorghum, −13% for barley and −60% for maize depending on the location, future climate scenarios and projected year (Porter *et al.* 2014).

Water is considered as a powerful indicator of ecological sustainability and economic prosperity (Kumar *et al.* 2013). Seventy percent of the Earth's surface is covered with water but 97.3% of the total water on Earth is saline, and only 2.7% is available as fresh water (Kumar *et al.* 2013). Almost 85% of all the water taken from rivers, lakes, streams and aquifers in India and in many of the developing countries is used for agriculture (Mohile & Goel 1996). The influence of global warming and climate change on the regional hydrological cycle would affect water resources and reduce the availability and reliability of water supplies in many places which are already subject to water scarcity. The per capita annual availability of water in India is expected to reduce to 1,465 m^3 by 2025 and 1,235 m^3 by 2050 (Kumar *et al.* 2013). Projected impacts of climate change on hydrology and water resources may be different in different river basins depending upon the hydrological model, climate change scenarios and downscaling approaches used (Gosain *et al.* 2006, 2011; Islam *et al.* 2014).

WATER RESOURCES AND THEIR USE IN INDIA

India has a geographical area of 329 million ha which amounts to 4,000 billion cubic metres (BCM) of water from annual precipitation (Mall *et al.* 2006). Due to large spatial and temporal variability in the rainfall, distribution of water resources in India is highly skewed in space and time (Goyal & Rao 2018). Surface and groundwater resources have played an important role in the socio-economic development of India. Groundwater is an important source of irrigation (Patle *et al.* 2015). The static fresh groundwater reserves of the country have been estimated as 1,082 BCM. The dynamic component which is replenished annually has been assessed as 432 BCM. The overall contribution of rainfall to the country's annual groundwater resource is 68% and the share of other resources, such as canal seepage, return flow from irrigation, recharge from tanks, ponds and water conservation structures taken together is 32% (CGWB 2014). The primary sources of irrigation are canals, reservoirs and wells, including tube-wells. Groundwater provides about 61.6% of water for irrigation, followed by canals with 24.5% (CGWB 2014).

There are 12 major river basins in India with an individual catchment area of more than 10 Mha and a cumulative catchment area of 252.8 Mha (Pathak *et al.* 2014). The other rivers with a catchment area of more than 10 Mha are the Indus (32.1 Mha), Godavari (31.3 Mha), Krishna (25.9 Mha) and Mahanadi (14.2 Mha). The degree of development of ten river basins covering 75% of the total population will be over 60% by 2050. The total annual discharge in the rivers that flow in various parts of the country amounts to 1,869 km^3. Rivers do not remain at a high stage throughout the monsoon season, but only a spell of heavy rains lasting for a period of several hours to a few days may generate significant runoff in catchments (Kale 2003). Due to the increasing population in the country, the national per capita annual availability of water has reduced from 1,816 cubic metres in 2001 to 1,544 cubic metres in 2011 (CWC 2015).

About 20% of the irrigated cropland worldwide provides 45% of the world's food. Average yield per irrigated hectare is 2.2 times the yield of rain-fed agriculture. In the next 25 years, the world will be challenged to produce sufficient food to feed an additional 90 million people each year, as well as to meet increasing and changing food needs resulting from rising incomes (Roelofs 1998). However, the relentless increase in the demand for water for various purposes brought about by population growth and economic development, combined with increasing pollution of water supplies, has raised serious problems for the environment.

GROUNDWATER WITHDRAWAL AND IMPACT OF CLIMATE CHANGE

Groundwater supports about 60% of irrigated agriculture and is the major source of irrigation in the arid and semi-arid regions of the country (Shah 2009; Patle *et al.* 2015). Groundwater levels have declined tremendously during the last three decades in many parts of the country due to overexploitation mainly in the agriculturally intensive irrigated areas (Patle *et al.* 2015). Decreased groundwater irrigation would have severe detrimental effects on many basins, and groundwater extraction ratios of many basins are significantly high. The recharge patterns in these basins indicate that the groundwater use is not sustainable. The level of groundwater development is very high in the states of Delhi, Haryana, Punjab and Rajasthan, where groundwater development is more than 100% (Patle *et al.* 2015). This implies that in these states, the annual groundwater consumption is more than the annual groundwater recharge. In the states of Himachal Pradesh, Tamil Nadu and Uttar Pradesh and the Union Territory of Pondicherry, the level of groundwater development is 70% and above. In the rest of the states, the level of groundwater development is below 70%. Over the years, the usage of groundwater has increased in areas where the resource was readily available. In India, about 52% of irrigation consumption across the country is extracted from groundwater; therefore, it can be an alarming situation with a decline in groundwater and increase in irrigation requirement due to climate change (Pathak 2015). The Ministry of Water Resources of India has worked out the temporal periodic water requirements for different sectors (Table 1).

Globally, the rate of groundwater abstraction is increasing by 1% to 2% per year (WWAP 2012). If the world continues to use water at the current rates, it is estimated that demand could exceed supply by as much as 40% by 2030, putting both water and food security at risk. Demands on agricultural water are likely to increase in future as domestic, industry and environmental uses of water continue to grow. Therefore, judicious utilisation of available water resources in agriculture, given the due concern for water storage, conveyance and distribution, needs to be planned for the sustainability of agriculture throughout the water-scarce countries. The technologies to harvest rainwater at source (e.g., roof harvesting for domestic purposes) are to be made mandatory so that pressure on local distribution is minimised at least during the lean period. The integrated use of surface and groundwater, adoption of efficient water management techniques and existing schemes of modernisation should be strengthened. Large-scale adoption and use of drip, sprinklers and conjunctive water use irrigation methods need more attention, particularly for small and marginal farmers.

Table 1 | Total water requirements for various sectors at different periods of time

	Water demands (BCM)				
Sector	**1990**	**2000**	**2010**	**2025**	**2050**
Irrigation	437	541	688	910	1,072
Drinking (including livestock)	32	42	56	73	102
Industrial	–	8	12	23	63
Energy	–	2	5	15	130
Others	33	41	52	72	80
Total	502	634	813	1,093	1,447

ENHANCING WATER USE EFFICIENCY THROUGH CLIMATE-SMART WATER MANAGEMENT TECHNOLOGIES

Water-smart agricultural technologies integrate traditional and innovative practices, technologies and services that are relevant for a particular location to adopt climate change and variability (CIAT 2014). Location-specific water-smart technologies, either individually or in combination, have substantial potential to reduce climate change impacts on water resources with proper planning and implementation. A meta-analysis carried out for crop simulation under several climate scenarios showed that farm-level adaptations could increase crop yields by an average of 7 to 15% and water saving from 25 to 50% when compared to without adaptation (Challinor *et al.* 2014; Jain *et al.* 2014). Simple adaptation measures such as changes in crop sowing dates and adoption of irrigation technologies can result in higher yields with less variation than without adaptation (Finger & Schmid 2007). Altieri & Nicholls (2017) reported that traditional management systems combined with the use of agro-ecologically based management strategies (bio-diversification, soil management and water harvesting) could prove the only viable and robust path to increase the productivity, sustainability and resilience of agricultural production under predicted climate scenarios.

In view of the above, there is an urgent need to determine the impacts of climate change on crop production and water to develop possible innovative climate water-smart adoption technologies (Aggarwal *et al.* 2009).

Best management practices in agriculture and technologies, namely, minimum tillage, different methods of crop establishment, nutrient and irrigation management and residue incorporation can improve crop yields, improve the water and nutrient use efficiency and minimise the emissions of greenhouse gases from agricultural activities (Jat *et al.* 2014; Sapkota *et al.* 2014). Similarly, water-smart technologies, namely, micro-irrigation, furrow-irrigated raised bed, rainwater harvesting structure, reuse wastewater, cover crop method, partial root dry (PRD), deficit irrigation, greenhouse, laser land levelling and drainage management can also help farmers to reduce the impact of climate change and variability (Mittal 2012; Altieri & Nicholls 2017). National Initiative on Climate Resilient Agriculture (NICRA 2016) has suggested several interventions such as adoption of scientific water conservation methods, precise estimation of crop water requirement, irrigation scheduling, groundwater recharge techniques, use of drought tolerant varieties, adjusting the planting dates, modifying the fertiliser and irrigation schedules and adopting zero-tillage which may help farmers to achieve satisfactory crop yields, even in deficit rainfall and warmer years. It is therefore imperative to promote water saving practices in irrigated as well as rain-fed agriculture on a large scale. Consequently, many international organisations, national governments' research institutions, farmers' organisations, NGOs and private agencies throughout the world are focusing their efforts on the design, development of cost-effective and environmentally friendly water saving devices and improved water application methods to increase water use efficiency and water productivity.

Many factors influence the extent of adoption of smart water technologies such as socio-economic characteristics of farmers, the bio-physical environment of a particular location, and the attributes of new technologies (Campbell *et al.* 2012). The identification, prioritisation and promotion of available water-smart technologies considering local climatic risks and demand for technology are significant challenges for scaling out smart water technologies in diverse agro-ecological zones. Problems of water scarcity could adequately be addressed through the adoption of smart water management interventions and modern irrigation technologies to enhance water use efficiency by involving the combination of area-specific approaches for both supply and demand side management. In view of the above, this paper brings together the current technical knowledge for the successful implementation of smart water technologies for climate-smart sustainable agriculture.

CLIMATE WATER-SMART TECHNOLOGIES FOR NATIONAL AND INTERNATIONAL APPLICABILITY

To tackle the challenges of increasing food production and improving rural livelihoods, necessary measures should be undertaken for effective water management in rain-fed and irrigated regions. An integrated approach needs to be adopted for agricultural water management through adoption of innovative technologies with national and international applicability, such as rainwater harvesting, sprinkler and drip irrigation, laser land levelling, floating agriculture, floating solar panels, resources conservation farming, conveyance of water through underground pipeline systems, etc. Some important water-smart technologies are explained as follows.

Water harvesting

The term water harvesting infers the collection of inevitable runoff, efficient storage of harvested water, its application and optimum utilisation for maximising production. Rainwater harvesting aims to minimise the effects of variations in water availability and to enhance the reliability of the agricultural output. Water harvesting may be operated by collecting water in ponds, tanks and other storage tanks created for the specific purpose. Rainwater harvesting structures consist of dugout ponds, embankment type ponds, check dams, etc. Agronomic and engineering measures are beneficial for rainwater harvesting. For arable land at farm level, it may be done through agronomic methods such as contour cultivation, mulching, trench plantation, furrow irrigation, deep tillage, contour farming, raised bed techniques of cultivation, ridges, etc. On the other hand, engineering techniques include contour bunds, graded bunds, bench terraces, contour trenches, conservation ditches and broad bed and furrow systems, etc. Similarly, rainwater harvesting from the roofs of houses in urban and rural areas and rainwater harvesting from the sloped roofs of low-cost and hi-tech polyhouses are increasingly important, especially in the northeastern hill states of India.

Rainwater harvesting (RWH) is an adaptation strategy for people living with high rainfall variability both for domestic supply and to enhance crops, livestock and other forms of agriculture. Rockström *et al.* (2009) suggested that rainwater harvesting structures can be very useful for semi-arid and dry, as well as sub-humid regions, especially in the regions where water scarcity is caused by extreme variability of rainfall rather than the amount of rainfall. IPCC (2014) advocated that rainwater harvesting structures are extremely important for mitigating the impact on agriculture and increasing agricultural productivity.

Floating solar power plants

Floating solar power plants are a new emerging technology throughout the world. Solar panels are fastened to a rigid buoyant structure. Floating solar plants float on top of a body of water such as reservoirs, wastewater treatment ponds, etc. These solar panels are naturally cooled, and due to the increase in the temperature of panels being less as compared to rooftop solar power panels they give a higher performance. Floating solar panels are a source of clean, renewable electricity and help to minimise greenhouse gases. The floating solar panel structure shades the body of water and reduces evaporation from these ponds, reservoirs and lakes (Taboadaa *et al.* 2017). Another advantage of using floating solar power plants is that the ecology of the water body is not affected and it also reduces evaporation losses to about 70%. Thus, it helps to preserve water levels during extreme summers (Taboadaa *et al.* 2017). Solar panels act as a roof for the water bodies, so the water is not exposed to the sun and atmosphere. The growth of organic matter such as algae would decrease, as solar panels act as a cover for the water bodies. According to Hassan & Peirson (2016), in many parts of Australia, the annual average evaporation exceeds the annual precipitation by more than five times. A high rate of evaporation and a prolonged drought period is a significant threat to water availability for agricultural production. Covering of water bodies using recycled clean plastic containers as floating modular devices helps to mitigate evaporation. The concept of floating solar power plants is increasing in the USA, China, Japan, the UK, India and many more countries. Floating solar power plants are a new and emerging concept in India and have immense potential for overcoming the problem of energy and water crises in future.

Floating agriculture

Floating agriculture is an indigenous technique of farming which involves planting crops on soil-less floating rafts. This technique has enough potential to help farming communities in the flood-prone regions during floods and long-term waterlogged conditions (Chowdhury & Moore 2017). Historically, these rafts were made of composted organic material, including water hyacinth, algae straw and herbs. Water hyacinth (aquatic weed) is commonly used for constructing floating beds in different regions of Bangladesh. The floating gardens are used for agricultural production, for example, vegetables and spices for local communities. Because prime nutrients such as nitrogen, potassium and phosphorus are abundant in the floating beds, there is almost no need for fertiliser.

Additionally, water prevents vermination and almost no pesticides are applied. The productivity of floating vegetable cultivation is estimated to be ten times higher than on similar sized land-based agriculture. Floating cultivation would help to mitigate this situation and reduce the pressure on arable lands by turning the flooded and waterlogged areas into productive ones.

According to Chowdhury & Moore (2017), floating agriculture has greatly supported farming communities to adapt to adverse waterlogged conditions by allowing vegetable production for daily consumption, income generation, community mobilisation along with providing food and nutrition security in Bangladesh. Hoque *et al.* (2015) have reported the yield under floating agriculture for okra as 24.14 t/ha, spinach 22.66 t/ha, tomato 43.76 t/ha, cucumber 13.32 t/ha, bitter gourd 24.80 t/ha, and pumpkin 24.10 t/ha, respectively. Floating agriculture could help to control invasive aquatic weeds and minimise water pollution and eutrophication problems (Kutty *et al.* 2009).

Laser land levelling

Laser land levelling is a proven agricultural on-farm technology that not only reduces farm irrigation needs but is also highly useful to reduce irrigation time and increase water use efficiency. A more levelled and smooth soil surface reduces the consumption of seeds, fertilisers, chemicals and fuel. The use of a laser leveller for land levelling has increased many-fold in some states – Haryana, Punjab, Uttar Pradesh and Madhya Pradesh, etc. Laser levelling could save 20–25% of irrigation water (Naresh *et al.* 2011). Most of the farmers in the Haryana state of India hire the equipment on an hourly basis. Farmers pay between 600 and 700 rupees per hour to use the machinery. Wakchaure *et al.* (2015) reported that precision levelling significantly improved the soil and canopy micro-environment and favoured increasing the sorghum yield by 27–73% and substantially saved irrigation water (30.9%) compared to unlevelled fields.

Furrow irrigated raised beds

Raised beds of 1 to 1.5 m width alternating with furrows are often constructed for growing vegetables, medicinal and aromatic and cereal crops. Two rows of plants are usually raised on two sides of a bed or ridge. A furrow runs between two rows of the adjacent ridges of beds and supplies water to the plant rows. The method ensures saving a large amount of water. The surface soil of beds or ridges remains dry, and the creeping plants and their fruits are not damaged. Water from the furrow moves laterally into the soil below the bed or ridge to meet the crop need. It prevents the accumulation of salts at the base of plants and reduces the salt injury to crops in areas where raised bed and furrow salt is a problem. This method offers a more effective control over irrigation and drainage as well as rainwater management during the monsoon.

Re-use of wastewater in agriculture

Due to water scarcity in the agriculture sector, recycling of wastewater is becoming more popular to augment water demand for agriculture in many parts of arid regions of the world (Alrajhi *et al.* 2015). Re-use and recycling of municipal wastewater and industrial effluent are significant to minimise the pollution load in the receiving water and the reduction in the requirement of freshwater for various uses. Re-use of municipal wastewater after treatment is necessary to meet industrial water requirements and is being used for horticulture, watering of lawns and even for flushing public sewers and toilets. Freshwater resources can be preserved using municipal recycled wastewater and stormwater for irrigation. Phytorid is a wastewater treatment constructed wetland technology for the treatment of municipal, urban, agricultural and industrial wastewater. The system is based on specific plants, such as elephant grass (*Pennisetum purpurem*), cattails (*Typha* sp.), reeds (*Phragmites* sp.), *Cannas* sp. and yellow flag iris (*Iris pseudocorus*), normally found in natural wetlands with filtration and treatment capability. Some ornamental, as well as flowering plant species such as golden dhuranda, bamboo, nerium, colosia, etc., can also be used for treatment as well as landscaping purposes.

Deficit irrigation

Partial root drying (PRD) is a new irrigation and plant growing technique which improves water use efficiency without significant yield reduction. PRD involves alternate drying and wetting of subsections of the plant root zone by exploring the plant physiological and biochemical responses (Alrajhi *et al.* 2017). It requires part of the root system being exposed for drying soil while the remaining part is irrigated normally (Stoll *et al.* 2000). The wetted and dried sides of the root system are alternated with a frequency according to soil drying rate and crop water requirement. PRD irrigation technology is widely used in horticultural crops. Liu *et al.* (2008) investigated the effects of partial root-zone drying (PRD) compared with full irrigation (FI) and deficit irrigation (DI) on water use efficiency (WUE) for potted tomatoes and reported that PRD had a higher WUE than DI given the same irrigation water. Abdelraouf (2016) found that PRD is promising for application in arid regions for saving water of up to 50% from crop water requirements without reduction of crop yield.

Micro-irrigation: technology of more crops per drop of water

Drip irrigation is one of the advanced methods of irrigation by which water can be supplied directly into the root zone of the soil. There are several methods of pressure irrigation, such as sprinkler irrigation, centre pivot and LEPA, micro-jets, drip/micro- or trickle irrigation and surface or subsurface irrigation. Drip irrigation systems are more efficient than other surface irrigation methods in terms of water savings, yield and water use efficiency. There is an increase in crop yields and reduction in the cost of fertilisers, pesticides and power for irrigation when using this method of irrigation. Thus, drip irrigation minimises conventional losses such as deep percolation, runoff and evaporation. The total potential of micro-irrigation in India is estimated at around 69.5 Mha. However, the coverage of micro-irrigation is only 7.7 Mha (FICCI 2016). Under drip irrigation the area covered was 3.37 Mha while sprinkler irrigation total coverage area was 4.36 Mha ha.

Plastic mulching

Plastic mulching, a technique to cover the soil around the root zone of a plant with a plastic film, is a useful practice to restrict weed growth, conserve moisture and reduce the effect of soil-borne diseases. The states in India that have played a dominant part in implementing the mulching activity in horticulture are Manipur (21%), Assam (20%), Uttarakhand (17%) Meghalaya (13%) and Nagaland (12%), with a combined share of about 83% in the total programme of mulching. Plastic film mulch is one of the most extensively used forms of plasticulture, and it is currently used on a vast scale in China, India, Israel and Italy. While plastic mulch is used to enhance water savings of micro-irrigation in developed countries, its adoption in developing countries is often independent of micro-irrigation technology. China accounts for 40% of the world's plastic mulch use. Plastic mulch performs a variety of functions, including soil disinfestation by solar energy (solarisation); covering the soil for heat collection; preventing the growth of weeds; minimising evaporation and escape of fertiliser; repelling or attracting insects; and manipulating soil temperature. Gao *et al.* (2019) carried out a meta-analysis to quantify and analyse the effects of plastic film mulching and residual plastic on yield and water use efficiency (WUE) of maize, wheat, potato and cotton in China. They reported a significant increase in crop yield (24.32%) and WUE (27.63%). Use of plastic mulching increases the potato yield by 30.62% and WUE 30.34% in China.

Cloud seeding

Cloud seeding has been applied to many agricultural areas around the world where rain is scarce and needed for crop survival. It is a form of weather modification or making artificial rain from clouds. It is also used to suppress hail, and has been practised in Israel for the last 30 years and is being used in many other countries. Originally, seeding with the aid of silver iodide began with the use of ground incinerators. The process has been improved, and special aircraft are used for this purpose, including the use of brine as the seeding material. Bangsund & Leistritz (2009) analysed the economic impacts of cloud seeding on agricultural crops in North Dakota and reported that the cloud seeding increased the amount of precipitation and reduced the risk of hail in the western North Dakota counties. The attempts helped to improve agricultural production and were a huge economic benefit to the region. Cloud seeding is also helpful to prevent the development of hail storms which cause severe damage to crops. Seeding has had a significant effect on increasing rainfall in many areas, especially in the Kinneret Basin (Sharon 1977).

It is assumed that a significant increase of 10–15% in rainfall in the northern part of the country has materialised (Sharon 1977). However, it has been noted that the limited cloud occurrence in drought years limits the benefits of cloud seeding when most needed.

Greenhouse technology

Greenhouse crops are one of the most innovative modern agriculture technologies. Use of greenhouses is useful in conserving water while simultaneously enhancing agricultural productivity. Greenhouses offer a stable alternative to traditional open-air farming practices, as they allow for consistent, year-round crop growth, all while reducing water usage (Connor & Mehta 2016). It is one of the highest human-made forms of agricultural activity, because of its intense technological and bio-agronomic input in confined portions of the farm environment. Greenhouse farming reduces water consumption as compared to open-air agriculture, mainly due to reduced evapotranspiration rates inside greenhouses. Use of drip irrigation systems improves the efficiency of water usage. By increasing the efficiency of irrigation, drip irrigation systems reduce water usage by 30–50% when compared with regularly used surface irrigation (Harmanto *et al.* 2005; Connor & Mehta 2016).

Retaining stubble/low till technique

Retaining stubble/low till is a technique widely applied in China. In this technique, stubble from one crop is left on the field after that crop is harvested. The low till method can improve water use efficiency by reducing soil evaporation and increasing yields in comparison to traditional agronomic techniques.

Hydroponics and aeroponics

The hydroponic technique replaces the conventional method of growing plants in soil. In this method, the liquid nutrient medium is provided for the growth of plants. It minimises the use of fertiliser and irrigation but requires continuous monitoring of plants. The benefits of hydroponic agriculture include less growing time, minimal disease, higher yields and water efficiency. Use of hydroponics in a controlled environment helps to achieve year-round production. Hydroponics uses substantially less water as compared to soil farming. The nutrient film technique (NFT) system of hydroponics is mostly used for the successful production of leafy and other vegetables with 70–90% savings of water throughout the world (Sharma *et al.* 2018). Leading countries in hydroponic technology are the Netherlands, Australia, France, UK, Israel, Canada and the USA. Growers should be well-versed about plant growth, nutrient balances and cultural media characteristics.

Aeroponics is also a technique for growing plants in air and a humid environment without soil. This technique is an efficient way of controlling humidity, temperature, soil pH and water conductivity. In aeroponics, plant roots are suspended in the air. The main advantage of the aeroponics system is limited water consumption.

ADAPTATION STRATEGIES

Potential impacts of climate change depend not only on climate per se but also on the system's ability to adapt to change. Depending on the vulnerability of individual crops in an agro-ecological region and the growing season, crop-based adaptation strategies need to be developed, integrating all available options to sustain productivity. Scientists have already developed several technologies to cope with extreme events like high temperature, frost and limited and excess moisture stress conditions (Kumar *et al.* 2010). These available technologies could be integrated and used for reducing the adverse impacts of climate change and climate variability. Some possible adaptation strategies that are relevant to current climatic risks are described in Table 2.

Efficient use of water and its management in agriculture is very critical for adaptation to climate change. Under rising temperatures and fluctuating precipitation patterns, water will become a scarcer resource in several parts of the world. Therefore, the amalgamation of traditional wisdom and modern innovative water management and water saving techniques needs to be thoughtfully implemented for sustainable crop production in water-scarce areas. Serious efforts towards water conservation, water harvesting, improvement of irrigation accessibility and water use efficiency would help in the strategic planning and management of available water resources in the region. *In situ* and *ex situ* water conservation techniques, micro-irrigation systems and selection of appropriate need-based irrigation must be encouraged among the farmers with proper training and skill development. The principles of increasing water infiltration by improving soil aggregation, decreasing runoff by using contours, ridges, vegetative hedges and reducing soil evaporation by using crop residue mulch could be employed for better management of soil–water. Development of technologies along with higher investments would help improve water management efficiency. Well-timed management of deficit irrigation can make a substantial difference in crop productivity in regions with limited access to irrigation. In the non-irrigated areas, water conservation and water harvesting techniques need to be disseminated as an alternative for poor farmers. However, the adoption of such practices will require investments in capacity building and agricultural extension. Rainwater

Table 2 | Adaptation strategies for agriculture and irrigation sector

Agriculture adaptation strategies	Irrigation adaptation strategies
1. Assisting farmers in coping with current climatic risk	1. Increasing the availability of useable water
• Improving collection and dissemination of weather information	• Water harvesting and storage
• Establishment of a regional early warning system of climatic risks	• Increasing groundwater recharge
• Promoting insurance for climatic risk management	• Recycling wastewater
2. Intensifying food production systems	2. Increasing the efficiency of water use
• Bridging yield gaps in crops	• Laser levelling of irrigated areas
• Enhancing livestock productivity	• Micro-irrigation
• Enhancing fisheries	• Adjusting crop agronomy
3. Improving land and water management	3. Groundwater management
• Implementing strategies for more efficient water conservation and use	• Managed aquifer recharge
• Managing coastal ecosystems	• Rationing electrical power supply
• Increasing the dissemination of resource conserving technologies	• Integration of surface and groundwater resource
• Exploiting the irrigation and nutrient supply potential of treated wastewaters	
4. Enabling policies and regional cooperation	4. Water transfer between basins
• Integrating adaptation in current policy considerations	
• Providing incentives for resource conservation	
• Securing finances and technologies for adaptation	
5. Strengthening research for enhancing adaptive capacity	5. Trans-boundary cooperation between different states
• Evolving adverse climate tolerant genotypes	
• Evaluating the biophysical and economic potential of various adaptation strategies	
6. Use of information and communication technology in water resource management	

harvesting can meet water demand in water-scarce regions. Improved irrigation methods like drip irrigation, sprinkler irrigation and use of laser-aided land levelling methods can also help in increasing water-use efficiency. Laser-aided levelling provides smooth and levelled fields, which allows proper water distribution with negligible water loss and facilitates uniformity in the placement of seed/seedlings and fertiliser. It also helps in plant stand, enhanced nutrient use efficiency and increased crop yield (Pathak *et al.* 2012). In rural areas, rainwater harvesting programmes may be launched through the use of gully plug, contour bund, gabion structure, percolation tank, check dam, and recharge shaft and dug well recharge.

India is the second largest producer of paddy in the world after China. The area irrigated under rice crop is about 22 million hectares, which is about 49.5% of the total area under rice crop (Patle *et al.* 2017). Water requirement varies from 775 to 3,000 mm according to climate, soil, crop and water management practices followed in a region (Zawawi *et al.* 2010; Patle *et al.* 2017). Water management in rice is possible through improved cultivation methods such as alternate wetting and drying (AWD), direct-dry seeding, aerobic rice, non-flooded mulching cultivation, and the system of rice intensification (SRI) which also helps to reduce the emission of greenhouse gases and saves water (Pathak *et al.* 2003; Jain *et al.* 2014). Direct-seeded rice (DSR) could be a potential option for water saving and reducing CH_4 emission compared to conventional puddled transplanted rice. The system of rice intensification (SRI) appears to be a suitable and sustainable way of growing rice for resource-poor farmers, and besides, it also has the potential of being able to increase soil fertility through increased carbon pool and mitigation possibilities of greenhouse gases. Patle *et al.* (2016) reported that improvement in on-farm irrigation infrastructure and cultivation practices has vast potential to decrease the water and energy requirement in irrigated agriculture.

POLICY ANALYSIS AND SUGGESTION

There is an urgent need for strong policies and programmes to promote rainwater harvesting. These should target areas that are water scarce, those that have become highly dependent on groundwater, and where rapid declines in groundwater levels are taking place. Substantial funding is required for the creation of rainwater harvesting structures and given the costs and externalities involved, it calls for public support. Conditions of institutional success such as clear objectives, good interaction, adaptiveness, appropriate scale and compliance need to be addressed by the policies and programmes to ensure proper performance. The check dam movement in Rajasthan and Gujarat shows that community involvement in rainwater harvesting projects and activities is essential for success. It also shows that creating effective village institutions with active participation can go a long way in improving results. Other experiences indicate that to improve the impact of rainwater harvesting, it is necessary to go beyond natural resource management to add productivity enhancement activities. These may include measures to improve water use efficiencies such as drip and sprinkler irrigation, and promotion of appropriate crops, varieties and modern inputs to enhance physical productivity and economic returns. Further, to extend the benefits to landless and weaker sections in rain-fed areas, it is important to include an enterprise promotion component. Rainwater harvesting and watershed development undertaken with such a comprehensive policy approach would lead to more inclusive and sustainable water resource development and management in water-scarce areas.

CONCLUSION

Decreasing water availability, higher input costs and growing environmental concerns are issues that water resources managers will not be able to ignore in the future. Solutions will not be easy and are likely to be multifaceted. Managing water properly is certainly one of the major challenges of the 21st century. Water use in the agriculture sector has to reform to conserve water and other resources so that non-agricultural demand for water can be sustained. Efficient use of agricultural water can be ensured through different water-smart technologies to optimise productivity. There is a need to develop a policy framework for implementing the adaptation and mitigation options so that farmers are saved from the adverse impacts of climate change. To promote the adoption of climate-resilient strategies, we need to facilitate the transfer of climate water-smart technologies from developed to developing countries. Future agriculture has to be carried out smartly so that not only water but also other key input resources like labour, chemicals, etc. can be sustainably managed. Along with technological innovations, increased farmer awareness and the necessary policy support (e.g., water pricing and changes in water entitlements, etc.) will be essential to achieving the objectives.

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