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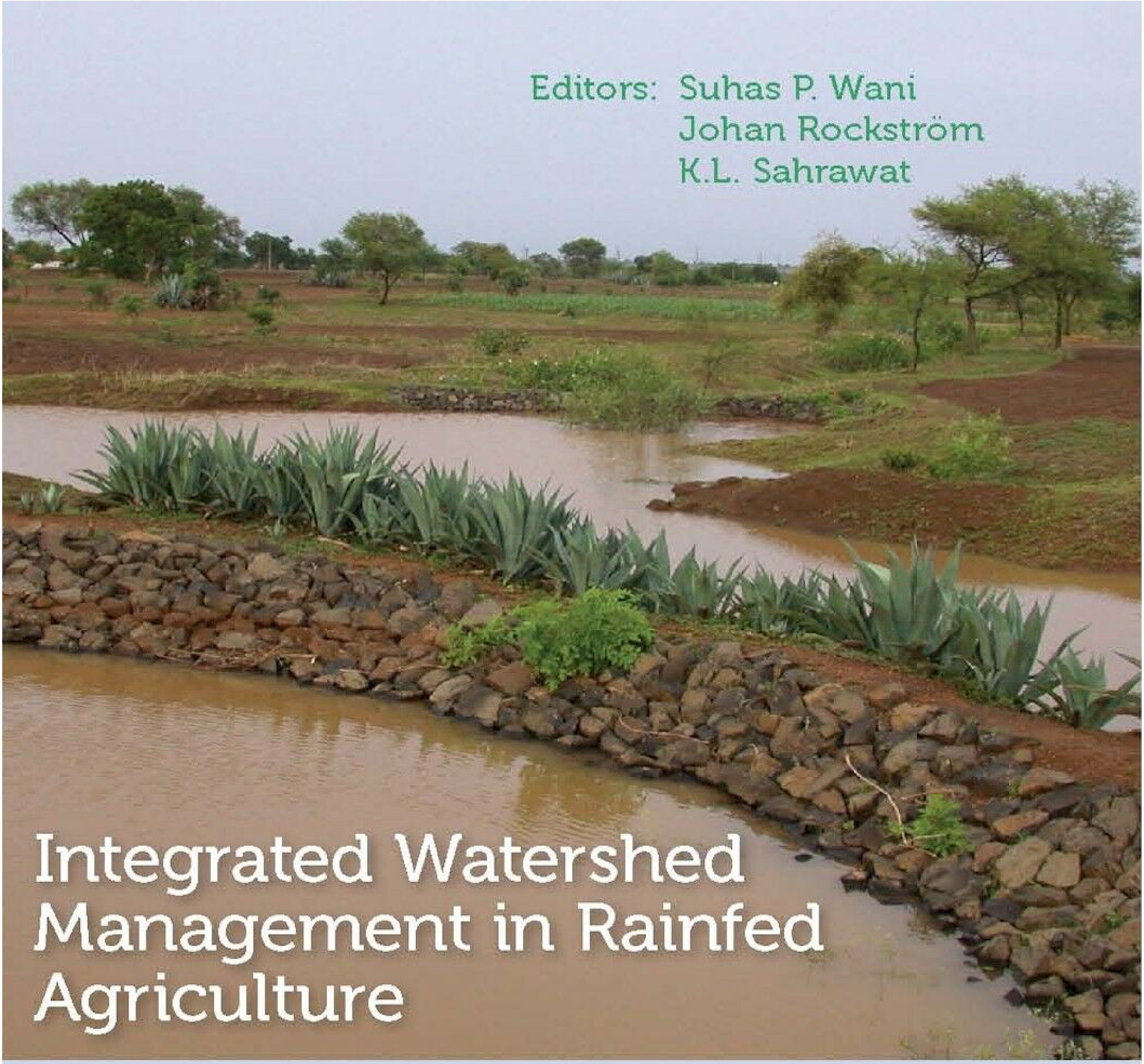

Integrated Watershed Management in Rainfed Agriculture

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Chapter 10

Increasing crop productivity and water use efficiency in rainfed agriculture

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10.1 INTRODUCTION

Globally rainfed agriculture is very important as 80% of the world's agricultural land area is rainfed and generates 58% of the world's staple foods (SIWI 2001). Most food for poor communities in the developing countries is produced in rainfed areas; for example, in sub-Saharan Africa (SSA) more than 95% of the farm land is rainfed, while the corresponding figure for Latin America is almost 90%, for South Asia about 60%, for East Asia 65%, and for Near East and North Africa 75%. In India, 66% of 142 million ha arable land is rainfed.

Rainfed agriculture in regions characterized by erratic rainfall is subject to large inherent water related risks, which make farmers less likely to invest in production enhancing inputs. If these risks can be lowered through investments in water management techniques to bridge dry spells, farmers' attitude regarding agricultural investments might also change. In rainfed areas, rainfall is the most prominent random parameter beyond farmers' control. Hence, rainfall is both a critical input and a primary source of risk and uncertainty for agricultural production (Rockström *et al.*, 2009). The Comprehensive Assessment of Water Management in Agriculture (Molden *et al.*, 2007) also points out to a large, untapped potential for upgrading rainfed agriculture and calls for increased investments in the sector. On-farm water balance analysis indicates that in semi-arid parts of India only 30–45% of rainfall is used for crop production in the traditional management systems (Wani *et al.*, 2003b). In SSA, less than 30% of rainfall is used as productive transpiration by crops. On severely degraded land, this proportion can be as small as 5% (Rockström and Steiner 2003). Thus, crop failures commonly blamed on "drought" might be prevented in many cases through better farm-level water management.

Current irrigation water withdrawals are already causing stress in many of the world's major river basins (Molle *et al.*, 2007). The world is facing a water crisis with little scope for further expansion of large-scale irrigation. Therefore, it is necessary to improve water management in rainfed agriculture not only to secure the water required for food production (Molden *et al.*, 2007) but also to build resilience for coping with the future water related risks and uncertainties (Rockström *et al.*, 2010). Some experts are predicting further decline in rainfall and amplification of extreme events (IPCC 2007). Thus, the current state-of-affairs and future scenarios underscore the fact that in the future food needs to be met with more efficient use of water resources for providing food and livelihoods for an increasing world population. Many non-water factors also limit production in rainfed agriculture. Production is also limited by labor shortages, insecure land ownership, inadequate access to capital for investments, and limited skills and abilities. As a result, actual production often falls short of potential output.

In this chapter, we briefly describe the concepts of water use efficiency (WUE) and dwell in detail on management options to enhance WUE as a strategy to bridge the yield gaps by following the integrated water resource management (IWRM) framework. The strategies for water harvesting and its use for crop intensification are dealt by Pathak *et al.* and balanced nutrient management strategies for enhancing WUE by Sahrawat *et al.* in this volume; whereas we have discussed in detail the case study results from different semi-arid tropical (SAT) regions to demonstrate the vast scope to bridge the wide existing yield gaps between achievable and current farmers' yields through enhanced WUE.

10.2 WATER USE EFFICIENCY: CONCEPTS AND DEFINITIONS

For increasing and sustaining crop productivity or income, it is important that all the resources input into the production system are efficiently used. Any concept of efficiency is a measure of the output from a given input. There are several definitions of WUE in the literature depending upon the purpose being achieved or the emphasis being placed on the problem being solved. In the biophysical sense, sustainable production refers to maximum economic yield per unit of water being applied or used by the crop, but in the economic sense, it is maximum net income per unit of water applied or used or monetary input to the crop. Some of the definitions of WUE used in the literature are described below.

- WUE_T is the amount of dry matter or marketable yield produced per unit of water taken up (transpiration) by plants. This is also known as transpiration efficiency or transpiration ratio (yield/transpiration).
- WUE_{ET} is the amount of dry matter or marketable yield produced per unit of evapotranspiration (ET) by the crop (yield/ET). ET is the sum of soil evaporation and transpiration by the crop during the season.
- WUE_I is the amount of dry matter or marketable yield produced per unit of irrigation amount applied to the crop (yield/irrigation). Sometimes this is also referred to as water application efficiency (WAE).
- WUE_R is the amount of dry matter or marketable yield produced per unit of rainfall received by the crop or cropping system (yield/rainfall). This is also known as rainfall use efficiency (RUE).
- $WUE_{(ET/R)}$ is the ratio of water used (ET) to the amount of rainfall received by the crop or cropping system during the growing period (ET/rainfall). It is also expressed as percent of rainfall.
- $WUE_{(R+I)}$ is the amount of dry matter or marketable yield produced per unit of rainfall plus irrigation [yield/(rainfall + irrigation)] received by the crop or cropping system during the cropping period.

For a comparative study of WUE of different crops or cropping systems in response to various management practices, equivalent yields of different crops or net income per unit of ET, amount of irrigation, rainfall or rainfall plus irrigation received by the crop or cropping system may be considered. In this chapter, we have considered WUE_{ET}, WUE_{R}, and $WUE_{(R+I)}$ of crops and cropping systems in terms of economic yield produced or net income per unit of water input or water used.

10.3 WATER BALANCE OF CROPS IN DIFFERENT RAINFED REGIONS

Rainfed regions vary in the amount of rainfall received, its distribution and water balance during the cropping season, thus providing varying opportunities for management of rainfall for enhancing crop yields. For example, total rainfall received during the cropping period in the arid, semi-arid, and subhumid zones of India is about 460, 730, and 980 mm, respectively (Table 10.1). The amount of water used (i.e., ET) by different crops varies with their duration in different zones. Surplus water (runoff + deep drainage) for water harvesting and reuse increases from arid to subhumid zone, thus providing variable opportunities for water management to increase productivity of one crop or to extend the season to grow second or third crop through supplemental irrigation. Thus different agroclimatic zones of rainfed area in India would require different land, water, and crop management practices to enhance overall WUE and crop productivity.

Table 10.1 Average values of water balance components of major rainfed crops in different agroclimatic zones of India[a]

Crop	*Agroclimate*	*Rainfall (mm)*	*Runoff (mm)*	*Deep drainage (mm)*	*Water use (mm)*	*Soil water change (mm)*
Sorghum	Arid	440	50	50	210	130
Pearl millet	Arid	395	55	65	160	115
Soybean	Arid	417	147	0	256	14
Groundnut	Arid	510	147	47	262	54
Pigeonpea	Arid	525	118	43	353	11
Mean		457	103	41	248	65
Sorghum	Semi-arid	795	168	150	337	141
Pearl millet	Semi-arid	671	122	139	248	162
Soybean	Semi-arid	725	195	65	356	108
Groundnut	Semi-arid	687	03	79	325	81
Pigeonpea	Semi-arid	785	183	83	495	24
Mean		733	174	103	352	103
Sorghum	Subhumid	1019	289	253	357	120
Pearl millet	Subhumid	807	230	190	263	123
Soybean	Subhumid	1043	334	205	397	107
Pigeonpea	Subhumid	1052	280	170	581	22
Mean		980	283	205	399	93

[a]Source: Recalculated from the data reported by Bhatia *et al.* (2006) and Murty *et al.* (2007).

10.4 GAPS IN PRODUCTIVITY AND WATER USE EFFICIENCY

In spite of uncertainty in water availability and low crop yields, there exists the potential to increase crop yields enormously in the semi-arid areas (Wani *et al.*, 2003a). Yield gap analyses undertaken by Comprehensive Assessment for major rainfed crops in the semi-arid regions of Asia and Africa and rainfed wheat in West Asia and North Africa (WANA) region revealed large yield gaps. Farmers' yields were lower by a factor 2–4 than achievable yields for major rainfed crops grown in Asia and Africa under water limiting conditions (Singh *et al.*, 2009). In the subhumid and humid tropical zones, agricultural yields in commercial rainfed agriculture exceed 5–6 t ha^{-1} (Rockström and Falkenmark 2000; Wani *et al.*, 2003a, 2003b). However, farmers' crop yields oscillate between 0.5 and 2 t ha^{-1} in the region with an average of 1 t ha^{-1} in SSA and 1–1.5 t ha^{-1} in SAT Asia, Central Asia, and WANA for rainfed agriculture (Rockström and Falkenmark 2000; Wani *et al.*, 2003a, 2003b). In India, large yield gaps for all the major rainfed crops have been observed and with the available technologies crop yields can be doubled, demonstrating that in addition to water availability other management factors also hold back the potential of rainfed crops (Table 10.2). The potential to increase productivity of crops increases from the arid to the subhumid agroclimate in the country. Similarly, large gaps exist in the RUE among crops in various agroclimatic zones. In a detailed study, Sharma *et al.* (2010) made a crop-specific assessment of the surplus runoff water available for harvesting across dominant rainfed districts of India. According to their estimates, a surplus rainfall of 114 billion m^3 was available for harvesting from the potential rainfed cropped area (excluding very arid and wet areas) of 28.5 million ha. If only a part of this harvested water is used for providing single supplemental irrigation to rainfed crops under improved management, an average increase of 50% in total production can be expected. Water harvesting and supplemental irrigation were found to be economically viable at the national level. However, the challenge to promote the adoption of technologies that can bridge the gaps in crop yields and WUE remains to be addressed.

Table 10.2 Average value of gap in yield and rainfall use efficiency for major rainfed crops in different agroclimatic zones of India[a]

		Yield (kg ha^{-1})			*Rainfall use efficiency (kg ha^{-1} mm^{-1})*		
Crop	*Agroclimate*	*Potential*	*Farmers'*	*Gap*	*Potential*	*Farmers'*	*Gap*
Groundnut	Arid	1480	1050	430	2.9	2.1	0.8
Groundnut	Semi-arid	3138	1088	2050	4.6	1.6	3.0
Pearl millet	Arid	830	605	225	2.1	1.5	0.6
Pearl millet	Semi-arid	2462	1086	1376	3.7	1.6	2.1
Pigeonpea	Semi-arid	1428	573	855	1.8	0.7	1.1
Pigeonpea	Subhumid	1550	770	780	1.5	0.7	0.7
Sorghum	Semi-arid	3195	885	2310	4.0	1.1	2.9
Sorghum	Subhumid	3550	890	2660	3.5	0.9	2.6
Soybean	Semi-arid	1960	1205	755	2.7	1.7	1.0
Soybean	Subhumid	2538	1061	1478	2.4	1.0	1.4

[a]Source: Recalculated from the data reported by Bhatia *et al.* (2006) and Murty *et al.* (2007).

10.5 INTEGRATED APPROACH TO ENHANCE PRODUCTIVITY AND WATER USE EFFICIENCY

To increase agricultural productivity with more efficient use of water, an IWRM framework is needed that can be operationalized through integrated genetic and natural resource management (IGNRM) approach. This approach includes implementation of both scientific and supporting solutions such as enabling policies, institutions, and socioeconomic aspects for enhancing adoption of technologies and practices by farmers and the implementing agencies. An inventory of strategies, purpose, and practices that increase productivity and WUE in the framework of IWRM for rainfed agriculture is given in Table 10.3 and discussed in detail in the following section.

Table 10.3 Inventory of technologies and management practices for increasing water use efficiency in rainfed agriculture

Strategy	*Purpose*	*Practices*
Rainfall management to secure water availability		
In-situ soil and water conservation and drainage improvement	Increasing soil water availability and minimizing drought and waterlogging stresses to crops	• Land surface management: Broad-bed and furrow (BBF), ridges and furrows, micro-basins, dead furrows, staggered trenches, contour farming, contour bunds, conservation furrows, and terraces • Tillage practices and conservation agriculture • Providing green cover to reduce runoff
Ex-situ water conservation and groundwater recharge	Conserving surplus water for supplemental irrigation to mitigate dry spells and to extend the cropping season	• Surface ponds: On-farm ponds, surface micro-dams, percolation ponds, check-dams, etc. • Groundwater recharging: Percolation ponds, check-dams, gully plugs, groundwater recharging structures, and subsurface ponds • Recharging of open wells
Increasing water use and water use efficiency		
Efficient supplemental irrigation	Mitigate dry spells, extend the cropping season, crop intensification and diversification	• Efficient water conveyance and application methods • Irrigation scheduling and deficit irrigation, conjunctive use of rainfall and irrigation • Intensification and diversification with high-value crops
Increasing soil water uptake	Increasing productivity and reducing water stress	• Improved crop agronomy: Early sowing, dry planting, seeding rate, plant geometry, crop choice • Balanced plant nutrition: Integrated nutrient management, water conservation and nutrient management • Crop protection: Integrated pest/disease management practices • Intercropping, crop rotations, crop diversification • Crop intensification: Intensification of rainy season fallows and rice fallows • Contingency and dynamic cropping

(*Continued*)

Table 10.3 Continued

Strategy	*Purpose*	*Practices*
Reducing soil evaporation	Minimizing unproductive losses	• Mulching (plastic, straw, or stone) and microclimate modification • Conservation agriculture
Increasing plant productivity per unit of water uptake	Increasing productivity and income per unit of water used by the crop	• Breeding high-yielding and drought tolerant varieties to increase water productivity
Promoting adoption of technologies		
Enabling policies	To enhance productivity, income, and efficient water use	• Greater investments in rainfed agriculture, sustained access to resources and inputs, financial support and selective incentives for rainfed and water efficient crops, water and electricity pricing, crop insurance • Efficient markets and infrastructure
Building institutions		• Enhancing participation of rural communities and bottom-up participatory approach • Building and strengthening community-based organizations • Collective and participatory water management • Consortium partners and efficient implementing agencies
Increasing awareness and capacity building	To increase knowledge and skills and provide options for efficient use of natural resources	• Efficient knowledge sharing • Building awareness about national and international policies • Building human capital particularly empowerment of women and underprivileged groups and institutional capacities

10.6 RAINFALL MANAGEMENT TO SECURE WATER AVAILABILITY

In the semi-arid and dry subhumid zone, it is not always the amount of rainfall that is the limiting factor for production (Klaij and Vachaud 1992; Hatibu *et al.* 2003; Wani *et al.* 2003b), it is rather the extreme variability of rainfall, with high rainfall intensities, fewer rain events, and poor spatial and temporal distribution of the rainfall. By contrast, in the arid zone, crop water needs often exceed the total rainfall, causing absolute water scarcity. In the semi-arid and subhumid agroecosystems, dry spells as short periods of drought during critical growth stages occur in almost every rainy season (Barron *et al.*, 2003; Rao *et al.*, 2003). By contrast, the meteorological droughts occur on average once or twice every decade. Frequencies of both meteorological droughts and dry spells are predicted to increase with climate change (IPCC 2007). While dry spells can be bridged through investments in appropriate water management techniques, crop yields cannot be sustained during a meteorological drought and different coping mechanisms are required. Some of the available options to enhance water availability are described below.

Figure 10.1 BBF system of soil and water conservation on a Vertic Inceptisol watershed (BW7 watershed) at ICRISAT, Patancheru, India (Source: Singh *et al.*, 2009)

10.6.1 In-situ soil and water conservation

Rainfed crop production, which uses infiltrated rainfall that forms soil moisture in the root zone, accounts for most of the crop water consumption in agriculture. Soil and water conservation, or in-situ water harvesting, has been the focus of most of the investment in water management in rainfed agriculture during the past 50 years. As in-situ water harvesting can be applied on any piece of land and is affordable by most smallholder farmers, the farmers can adopt these practices with little training (Wani *et al.*, 2003b; Sreedevi *et al.*, 2004). These management systems need to be in place prior to investing in ex-situ water harvesting options. Their implementation in the field depends on the characteristics of the soil, climate, farm size, capital, and availability of human and traction power resources. Some of the in-situ water conservation practices that can be implemented for increasing soil water availability are described.

10.6.1.1 Land surface management

Land smoothening and forming field drains are basic components of land and water management for conservation and safe removal of excess water. Broad-bed and furrow (BBF) system is an improved in-situ soil and water conservation and drainage technology for the Vertisols. This system is useful for clayey soils with low infiltration capacity as soil profile gets saturated and waterlogged with the progression of rainy season. The system consists of raised bed approximately 100 cm wide and shallow furrow about 50 cm wide laid out in the field with a slope of 0.4 to 0.8% (Figure 10.1). The BBF system helps in the safe disposal of excess water through furrows when there is high intensity rainfall with minimal soil erosion, at the same time it serves as land surface treatment for in-situ moisture conservation. Contour farming is practiced on lands having medium slope (0.5–2.0%) and permeable soils, where farming operations such as plowing and sowing are carried out along the contour. The system helps to reduce

Table 10.4 Effect of land configuration on productivity of soybean- and maize-based system in the watersheds of Madhya Pradesh, India, 2001–05[a]

		Grain yield ($t\,ha^{-1}$)		
Watershed location	*Crop*	*Farmers' practice*	*BBF system*	*Increase in yield (%)*
Vidisha and Guna	Soybean	1.27	1.72	35
	Chickpea	0.80	1.01	21
Bhopal	Maize	2.81	3.65	30
	Wheat	3.30	3.25	16

[a]Source: Singh *et al.* (2009).

Table 10.5 Rainfall use efficiency of different cropping systems under improved land management practices in Bhopal, Madhya Pradesh, India[a]

	Rainfall use efficiency ($kg\,ha^{-1}\,mm^{-1}$)	
Cropping system	*Flat-on-grade*	*BBF system*
Soybean–chickpea (sequential)	8.2	11.6
Maize–chickpea (sequential)	8.9	11.6
Soybean/maize–chickpea (intercrop and sequential)	8.9	10.9

[a]Source: Singh *et al.* (2009).

the velocity of runoff by impounding water in series of depressions and thus decrease the chance of developing rills in the fields. Conservation furrows is another promising technology for Alfisols having moderate slope (0.2–0.4%) and receiving seasonal rainfall of 500–600 mm. It comprises a series of dead furrows across the slope at 3 to 5 m intervals, where the size of furrows is about 20 cm wide and 15 cm deep. Contour bunding is recommended for medium to low rainfall areas (<700 mm) on permeable soils with less than 6% slope. It consists of a series of narrow trapezoidal embankments along the contour to reduce and store runoff in the fields. The BBF system and contour bunds must be in place before sowing, while conservation furrows and other operations along the contour can be carried out at sowing or later during the crop growing season.

On-farm trials on land management of Vertisols of Central India revealed that BBF system resulted in 35% yield increase in soybean during the rainy season and yield advantage of 21% in chickpea during the postrainy season when compared with farmers' practice. Similar yield advantage was recorded in maize and wheat rotation under BBF system (Table 10.4). Yield advantage in terms of RUE was also reflected in the cropping system involving soybean-chickpea, maize-chickpea, and soybean/maize-chickpea under improved land management systems. The RUE ranged from 10.9 to 11.6 $kg\,ha^{-1}\,mm^{-1}$ across cropping systems in BBF system compared to 8.2 to 8.9 $kg\,ha^{-1}\,mm^{-1}$ in flat-on-grade system of cultivation on Vertisols (Table 10.5). The benefits due to conservation furrow landform treatment were also evaluated on Alfisols in the Haveri, Dharwad, and Tumkur districts of Karnataka, India. Yield advantage of 15 to 20% was recorded in maize, soybean, and groundnut with conservation furrows over farmers' practices (Table 10.6).

Table 10.6 Effect of improved land and water management on crop productivity in the Sujala watersheds of Karnataka, India during 2006–07[a]

Watershed	*Crop*	*Grain yield ($t\,ha^{-1}$)* *Farmers' practice*	*Conservation furrows*	*Increase in yield (%)*
Haveri	Maize	3.57	4.10	15
Dharwad	Soybean	1.50	1.80	20
Kolar	Groundnut	1.05	1.22	16
Tumkur	Groundnut	1.29	1.49	15

[a]Source: Singh *et al.* (2009).

Table 10.7 Effect of summer plowing and other agronomic practices on yield and water use efficiency (WUE) of pearl millet[a]

	Grain yield ($kg\,ha^{-1}$)		*WUE_{ET} for grain yield ($kg\,ha^{-1}\,mm^{-1}$)*	
Treatment	*1997*	*1998*	*1997*	*1998*
No summer plowing	1880	1912	7.34	7.00
Summer plowing	2173	2292	8.41	7.96
Summer plowing + farmyard manure + insecticide + herbicide	2270	2509	8.73	8.50
CD ($P = 0.05$)	190	155		

[a]Source: Jat and Gautam (2001).

10.6.1.2 Tillage

Tillage roughens the soil surface and breaks apart any soil crust or compaction. This leads to increased water storage by increased infiltration into the soil as well as increased water loss by evaporation compared with residue-covered surface. After initial water loss, tilled surface soil also acts as soil mulch and reduces loss of water from the subsoil because of break of continuity of capillaries. More aggressive and frequent tillage also damages the soil structure, reduces macro porosity and reduces rainwater infiltration into the soil through the effect on hydraulic conductivity (Hatfield *et al.*, 2001).

Jat and Gautam (2001) studied the productivity and water use of rainfed pearl millet as influenced by summer plowing and in-situ moisture conservation practices under the semi-arid conditions of New Delhi, India. Summer plowing alone or in combination with soil fertility management and crop protection practices increased productivity and WUE of pearl millet than no summer plowing (Table 10.7). Jat *et al.* (2006) studied the effects of tillage practices on the productivity and WUE of maize on a sandy loam in the Bhilwara region of western India. Tillage practice with summer disc plow, followed by cultivator was more beneficial to the farmer in terms of increased maize yield and higher net returns despite the higher cost of cultivation. This practice also reduced runoff by 32.9%, soil loss by 66.4%, and increased WUE by 85.7% over the practice of tilling the soil using cultivator two times at the time of sowing.

These studies indicated that summer plow on sandy loam soils of North India increases productivity and WUE of dryland crops.

Oswal and Dakshinamurti (1976) investigated the effects of subsoiling plus 2 disking, chisel-plow plus 2 disking, moldboard plowing plus 2 disking, three surface cultivations or fallowing on the yield and WUE of pearl millet and mustard; WUE was highest with subsoiling. Jin *et al.* (2007) evaluated various tillage practices on the silt loam soils of the loess plateau in China. Four years of no till followed by one subsoiling with soil cover reduced soil compaction, increased WUE (+10.5%) and yield (+12.9%) of maize and wheat as compared to traditional tillage methods, and also provided 49% economic benefit for maize and 209% for the wheat crop. The above studies indicate that tillage practices increase infiltration, reduce soil evaporation, enhance root penetration and extraction of water and nutrients from the soil profile, and increase productivity and WUE.

10.6.1.3 Conservation agriculture

The three basic elements of conservation agriculture are: (1) No or minimum tillage without significant soil inversion; (2) Retention of crop residues on the soil surface; and (3) Growing crops in rotations appropriate to the soil-climate environment and socioeconomic conditions of the region. This practice promotes in-situ conservation of rainfall, reduces soil evaporation, moderates soil temperature, improves crop productivity and soil quality through reduced soil erosion, and improves soil organic matter and other soil physical, chemical, and biological properties (Rockström and Steiner 2003; Rockström *et al.*, 2009).

Some form of conservation agriculture is practiced on 40% of the rainfed farm land in the United States and has generated an agricultural revolution in several countries in Latin America (Derpsch 2005; Landers *et al.*, 2001). Examples from SSA show that converting from plow to conservation agriculture results in yield improvements ranging between 20% and 120%, with water productivity improving from 10% to 40% (Table 10.8) (Rockström *et al.*, 2009). In northern China on the loess plateau conservation tillage (no tillage and straw management) increased wheat crop productivity and WUE by up to 35% compared to conventional tillage, especially in the low rainfall years. Conservation tillage is a more sustainable farming system in terms of increased productivity, improved soil structure, and positive environmental impacts in the dry farming areas in northern China (Li HongWen *et al.*, 2007; Wang *et al.*, 2007). Other advantages of non-inversion tillage systems include saving in labor needed for plowing. The potential disadvantages include higher costs of pest and weed control, the cost of acquiring new management skills, and investments in new planting equipment. Conservation agriculture can be practiced on all soils, especially light soils and does not require water harvesting structures. It increases productivity, sustainability, and efficient use of natural resources (Rockström *et al.*, 2009).

10.6.2 Water harvesting and groundwater recharge

In medium to high rainfall areas, despite following in-situ moisture conservation practices, rainfall runoff occurs due to high intensity storms or water surplus opportunities after filling up the soil profile. This excess water should be harvested in surface ponds

Table 10.8 Average maize grain yield under various tillage and conservation farming systems in Ethiopia, 1999–2003[a]

Treatment	*Fertilized Mean yield (kg ha^{-1})*	*n*	*Non-fertilized Mean yield (kg ha^{-1})*	*n*
Ripping + ridging	1775 (111)^{a}	32	1462 (133)^{bc}	19
Ripping + wing-plow	1609 (128)^{ab}	19	1403 (179)^{ab}	9
Ripping + subsoiling	1540 (127)^{abc}	25	1266 (141)^{bc}	19
Conventional/Maresha	1458 (100)^{bc}	32	1258 (131)^{c}	18

[a]Standard error (SE) is given in paranthesis. Values are significantly different at $P < 0.05$.
Source: Rockström *et al.* (2009).

Figure 10.2 Water harvesting structure in Wang Chai watershed in Thailand (Source: ADB 2006)

for recycling through supplemental irrigation or the groundwater should be recharged for later use in the postrainy season. The size and shape of the water harvesting structure and its location in the landscape depend upon the topography, amount of runoff expected, supplemental irrigation needs, socioeconomic condition of the farmers, and the equity concerns. Various types of water harvesting structures were tried in the Adarsha watershed in Kothapally village in Andhra Pradesh, India, Tad Fa watershed in Thailand, and Thanh Ha watershed in Vietnam with the participation of farmers (Figure 10.2). Water harvesting in these structures resulted in increase in groundwater levels (Figure 10.3). Additional water resource thus created was used by the farmers to provide supplemental irrigation to the crops especially to postrainy season crops such as chickpea or to grow high-value crops such as vegetables in these watersheds. Small, low-cost, and well distributed water harvesting structures throughout the toposequence in the watershed area provided equity and benefited more number of farmers than the large size structures which benefit only a few selected farmers (Wani *et al.*, 2003c, 2008; Pathak *et al.*, 2009).

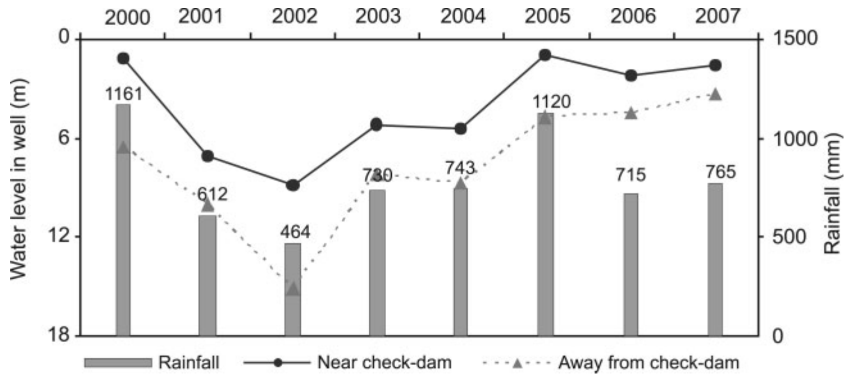

Figure 10.3 Influence of water harvesting structures on groundwater levels in Adarsha watershed, Kothapally, India (Source: Pathak *et al.*, 2009)

10.7 INCREASING WATER USE AND WATER USE EFFICIENCY

10.7.1 Efficient supplemental irrigation

In the semi-arid and subhumid agroecosystems, dry spells occur in almost every season. These dry spells need to be mitigated to save the crop from drought and minimize the climate risks to crop production in rainfed systems. Supplemental irrigation is also used to secure harvests or to provide irrigation to the second crop during the postrainy season. Supplemental irrigation systems are ex-situ water harvesting systems comprising surface ponds or recharged groundwater. Efficient use of water involves both the timing of irrigation to the crop and efficient water application methods. Broadly, the methods used for application of irrigation water can be divided into two types, viz., surface irrigation systems (border, basin, and furrow) and pressurized irrigation systems (sprinkler and drip). In the surface irrigation system, the application of irrigation water can be divided into two parts: (1) Conveyance of water from its source to the field; and (2) Application of water in the field.

10.7.1.1 Conveyance of water to the field

In most SAT areas, the water is carried to cultivated fields through open channels, which are usually unlined and therefore, a large amount of water is lost through seepage. On the SAT Vertisols, generally there is no need of lining the open field channels as the seepage losses in these soils are low mainly due to very low saturated hydraulic conductivity in the range of 0.3 to 1.2 $\mathrm{mm\,h^{-1}}$ (El-Swaify *et al.*, 1985). On Alfisols and other sandy soils having more than 75% sand, the lining of open field channel or use of irrigation pipes is necessary to reduce the high seepage water losses. The uses of closed conduits (plastic, rubber, metallic, and cement pipes) are getting popular especially with farmers growing high-value crops, viz., vegetables and horticultural crops (Pathak *et al.*, 2009).

Table 10.9 Grain yield of chickpea in different treatments on Vertisols at ICRISAT, Patancheru, Andhra Pradesh, India[a]

Treatment	*Mean depth of water application (cm)*	*Grain yield (kg ha^{-1})*
No supplemental irrigation	0	690
One supplemental irrigation on uncultivated furrows	6.3	920
One supplemental irrigation on cultivated furrow	4.6	912
SEM		19
CV (%)		5.55

[a]Source: Pathak *et al.* (2009).

10.7.1.2 Methods of application of supplemental water on SAT Vertisols

Formation of deep and wide cracks during soil drying is a common feature of the SAT Vertisols. The abundance of cracks is responsible for high initial infiltration rates (as high as 100 mm h^{-1}) in dry Vertisols (El-Swaify *et al.*, 1985). This specific feature of Vertisols makes efficient application of limited supplemental water to the entire field a difficult task. Among the various systems studied at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, the BBF system was found to be most appropriate for applying irrigation water on Vertisols. As compared to narrow ridge and furrow, the BBF system saved 45% of the water without affecting crop yields. Compared to narrow ridge and furrow and flat systems, the BBF system had higher WAE, water distribution uniformity, and better soil wetting pattern (Pathak *et al.*, 2009). Studies conducted to evaluate the effect of shallow cultivation in furrow on efficiency of water application showed that the rate of water advance was substantially higher in cultivated furrows as compared to that in uncultivated furrows. Shallow cultivation in moderately cracked furrows before the application of irrigation water, reduced the water required by about 27% with no significant difference in chickpea yields (Table 10.9).

10.7.1.3 Efficient application of supplemental water on SAT Alfisols

On Alfisols, surface irrigation on flat cultivated fields results in very poor distribution of water and high water loss. The wave-shaped BBF system, with checks at every 20 m length along the furrows, was found to be most appropriate for efficient application of supplemental water and increasing crop yields. The moisture distribution across the beds was uniform in the wave-shaped BBF system with checks compared to normal BBF system (Pathak *et al.*, 2009). Sorghum yield in wave-shaped BBF system with checks was higher at every length of run compared to normal BBF (Table 10.10). When irrigation water was applied in normal BBF system on Alfisols, the center of the broad-bed remained dry. The center row crop did not get sufficient irrigation water, resulting in poor crop yields. In another experiment on Alfisols, normal BBF system (150 cm wide) was compared with narrow ridge and furrow system (75 cm wide). The narrow ridge and furrow system performed better than BBF system both in terms of uniform water application and higher crop yields. Therefore, for Alfisols, the

Table 10.10 Sorghum grain yield as affected by water distribution in different surface irrigation systems on Alfisols[a]

	Grain yield (t ha^{-1})	
Length of run (m)	*Normal BBF*	*Wave-shaped broad-bed with check in furrow*
0	2.07	2.52
20	2.38	3.91
40	2.56	4.42
60	3.06	4.54
80	3.26	4.53
100	3.08	4.42

[a]Source: Pathak *et al.* (2009).

wave-shaped broad-bed with check in the furrow is the most appropriate land surface configuration for efficient application of supplemental irrigation water, followed by narrow ridge and furrow system (Pathak *et al.*, 2009).

The improved surge flow irrigation method can also be used for improving the performance of furrow irrigation. This system saves water, uses less energy, and improves water productivity. With proper planning and design surge flow system can be extensively used for efficiently irrigating high-value crops grown using the ridge and furrow landform (Singh 2007). Modern irrigation methods, viz., sprinklers and drip irrigation, can play vital roles in improving water productivity. These irrigation systems are highly efficient in water application and have opened up opportunities to cultivate light-textured soils with very low water-holding capacity and in irrigating undulating farm lands. The technology has also enabled regions facing limited water supplies to shift from low-value crops with high water requirements such as cereals to high-value crops with moderate water requirements such as fruits and vegetables (Sharma and Sharma 2007).

Burney *et al.* (2010) studied the role of solar-powered drip irrigation systems in enhancing food security in the Sudano-Sahelian region of Africa and concluded that the system can provide substantial economic, nutritional, and environmental benefits to the population. Implementation of these improved irrigation techniques can be used to save water and energy, and increase crop yields. However, currently the use of these improved irrigation methods are limited, primarily due to the high initial cost. Favorable government policies, availability of credit, institutional support, and training of farmers are essential for popularizing these irrigation methods.

10.7.1.4 Scheduling of irrigation and deficit irrigation

Srivastava *et al.* (1985) studied the response of postrainy season crops to supplemental irrigation grown after maize or mung bean on a Vertisol. The highest WAE was recorded for chickpea (5.6 kg mm^{-1} ha^{-1}), followed by chili (4.1 kg mm^{-1} ha^{-1}), and safflower (2.1 kg mm^{-1} ha^{-1}) (Table 10.11). It was concluded that a single pre-sowing irrigation to the sequential crops of chickpea and chili was profitable on Vertisols. Average additional gross returns due to supplemental irrigation were about ₹1630 ha^{-1} for safflower, ₹7900 ha^{-1} for chickpea, and ₹14600 ha^{-1} for chili.

Table 10.11 Response of sequential crops in the postrainy season to supplemental irrigation on a Vertisol watershed at ICRISAT, Patancheru, Andhra Pradesh, India, 1981–85[a]

Cropping system (sequential)	*Yield (kg ha^{-1})*		*Water application efficiency (kg mm^{-1} ha^{-1})*
	Irrigated	*Increase due to irrigation*	
Maize-chickpea	1540	493	5.6
Mung bean-chili	1333	325	4.1
Maize-safflower	1238	165	2.1

[a]Source: Pathak *et al.* (2009).

Table 10.12 Grain yield response of cropping systems to supplemental irrigation on an Alfisol watershed at ICRISAT, Patancheru, Andhra Pradesh, India, 1981–82[a]

Yield with irrigation (kg ha^{-1})	*Yield increase (kg ha^{-1})*	*WAE (kg ha^{-1} mm^{-1})*	*Yield with irrigation (kg ha^{-1})*	*Yield increase (kg ha^{-1})*	*WAE (kg ha^{-1} mm^{-1})*	*Combined WAE (kg ha^{-1} mm^{-1})*
Intercropping system						
Pearl millet			Pigeonpea			
2353	403	10.0	1197	423	5.3	6.8
Sorghum			Pigeonpea			
3155	595	14.9	1220	535	6.7	9.4
Sequential cropping system						
Pearl millet			Cowpea			
2577	407	10.2	735	425	5.3	6.9
Pearl millet			Tomato			
2215	350	8.8	26250	14900	186.3	127.1

[a]Source: Pathak and Laryea (1991).
Irrigation of 40 mm each was applied.

Impressive benefits have also been reported from supplemental irrigation of rainy and postrainy season crops on Alfisols at ICRISAT, Patancheru, India (El-Swaify *et al.*, 1985; Pathak and Laryea 1991). The average WAE for sorghum (14.9 kg mm^{-1} ha^{-1}) was more than that for pearl millet (8.8 to 10.2 kg mm^{-1} ha^{-1}) (Table 10.12). An intercropped pigeonpea responded less to irrigation and its average WAE ranged from 5.3 to 6.7 kg mm^{-1} ha^{-1} for both sorghum/pigeonpea and pearl millet/pigeonpea intercrop systems. Tomato responded very well to water application with an average WAE of 186.3 kg mm^{-1} ha^{-1} (Table 10.12).

For the sorghum/pigeonpea intercrop, two irrigations of 40 mm each, gave an additional gross return of ₹9750 ha^{-1}. The highest additional gross return from supplemental irrigation was obtained by growing tomato (₹58300 ha^{-1}). These results indicate that on Alfisols, significant returns can be obtained from relatively small quantities of supplemental water.

The above studies indicate that on Alfisols, the best results from limited supplemental irrigation were obtained during the rainy season. On Vertisols in medium to high rainfall areas, pre-sowing irrigation for postrainy season crops was found to be the

Table 10.13 Effect of irrigation on sorghum (CSH6) yield (kg ha^{-1}) on different sections of the slope on Alfisols at ICRISAT, Patancheru, India, 1985–1986[a]

	Grain yield (kg ha^{-1})									
	Upper section (0–20 m)		*Middle section (20–40 m)*		*Lower section (40–60 m)*		*Average*		*WAE[b] (kg mm^{-1} ha^{-1})*	
Treatment	*1985*	*1986*	*1985*	*1986*	*1985*	*1986*	*1985*	*1986*	*1985*	*1986*
Rainfed	1058	2220	1618	2110	1710	2140	1659	2150	–	–
Full irrigation[c]	3716	3404	3516	3200	2960	3458	3390	3352	6.9	7.5
LID system	3413	3090	2600	2710	2000	2110	2671	2636	12.1	9.2

[a] Source: Pathak *et al.* (2009).
[b] Water application efficiency (WAE) = Increase in yield due to irrigation/Depth of irrigation
[c] Five irrigations totalling 250 mm and 4 irrigations totalling 130 mm were applied during 1985 and 1986 respectively on full irrigation and LID (upper section) treatments on area basis.

most beneficial. The best responses to supplemental irrigation were obtained when irrigation water was applied at critical stages of the crop. To get the maximum benefit from the available water, growing high-value crops (viz., vegetables and horticultural crops) is becoming popular even with poor farmers (Pathak *et al.*, 2009). According to Oweis (1997), supplemental irrigation of 50-200 mm can bridge critical dry spells and stabilize yields in arid to dry subhumid regions. The potential yield increase in supplemental irrigation varies with rainfall. An example from Syria illustrates that improvements in yields can be more than 400% in arid regions (Oweis 1997). Several studies indicate that supplemental irrigation systems are affordable by small-scale farmers (Fan *et al.*, 2000; Fox *et al.*, 2005). However, policy framework, institutional structure, and human capacity similar to those for full irrigation infrastructure are required to successfully apply supplemental irrigation in rainfed agriculture.

10.7.1.5 Conjunctive use of rainfall and limited irrigation water

Stewart *et al.* (1983) developed a limited irrigation dryland (LID) system for efficient use of limited irrigation water for crop production. The objective of the LID system concept was to maximize the combined use of growing-season rainfall, which varies for any given year, with a limited supply of irrigation water. This system was studied at ICRISAT, Patancheru, India for rainy season sorghum on Alfisols. Results demonstrated the usefulness of LID system in the application of limited water under uncertain and erratic rainfall conditions. The LID system increased both crop yields and WAE during the two years of study (Table 10.13).

10.7.1.6 Supplemental irrigation and crop intensification or diversification

The primary constraints for food security in developing countries are low productivity per unit area, shrinking land and water sources available for cropping, and escalating costs of crop production. Under these circumstances, crop diversification can be useful to increase crop output under different conditions of available resources either

Table 10.14 Crop diversification with high-value crops under supplemental irrigation in the Ringnodia watershed, Madhya Pradesh, India[a]

Crop	*Area covered (ha)*	*Yield (t ha^{-1})*	*Net income (₹ ha^{-1})*
Potato	8.3	17.5	29130
Onion	1.0	25.2	42000
Garlic	1.5	7.6	15750
Hybrid tomato	1.5	66.8	55000
Coriander	2.9	6.1	12700

[a]Source: Singh *et al.* (2009).

through broadening the base of the system by adding more crops coupled with efficient management practices or replacing the traditional crops by high-value crops. Crop diversification allows realization of the real value of improved water availability through watershed programs either through growing high-value crops like vegetables or more number of crops with supplemental irrigation. However, crop diversification takes place automatically from traditional agriculture to high-value/commercial agriculture at the field level once the water availability is improved. On-farm survey in Ringnodia watershed in Madhya Pradesh revealed the spread of high-value crops like potato, coriander, garlic, etc. and increase in net income from farming activities once the scope for supplemental irrigation was established in the watershed (Table 10.14).

10.7.2 Increasing soil water uptake

10.7.2.1 Improved crop agronomy

Many studies have clearly shown that delayed planting after the site-specific optimum date often results in grain yield losses of 4 to 7% per week. Yield reductions in late-sown wheat is often attributed to inadequate tillering and reduced transpiration late in the season (Doyle and Fischer 1979). High seeding rates can offset much of the adverse effect of late seeding (Khalifa *et al.*, 1977; Doyle and Fischer 1979). For other situations the cause for low yields may be related to occurrence of pests and diseases associated with the sowing date. Off-season tillage and early bed preparation can be of considerable benefit for timely sowing. In southern India below 18°N latitude, advancing the sowing of postrainy season crops is a simple and effective practice of increasing WUE.

In dryland agriculture, the adjustments in plant population and row spacing are often needed for optimizing the use of light and water and to achieve high harvest index of crops. However, these practices are crop, season, and site specific considering the water availability environment. A crop with high plant density uses soil moisture early in the season resulting in low grain yield. On the other hand, a crop with low plant density does not fully extract the available soil moisture and thus gives reduced yields. Steiner (1986) showed that high plant population of dryland sorghum significantly reduced grain yield because of severe decrease in harvest index. However, there was no difference in the grain yield under low and medium plant populations. These results show that harvest index and amount of water extracted can be affected by planting

Table 10.15 Effects of sulfur and micronutrient amendments on yields of selected field crops in Andhra Pradesh, India[a]

	Yield (kg ha^{-1})		
Crop	*Control*	*Sulfur + micronutrients*	*Increase (%) over control*
Maize	2800	4560	79
Mung bean	770	1110	51
Castor	470	760	61
Groundnut (pod)	1430	1825	28

[a]Source: Singh *et al.* (2009).

geometry, but the range is very wide before grain yield is severely affected. Therefore, the best strategy is to select a combination of moderate plant population and row width for higher yields and higher WUE. And these combinations are determined by the crop or variety, season, and the site where the crop is grown.

10.7.2.2 Balanced plant nutrition

Besides water scarcity, low fertility is one of the major causes for low productivity under rainfed system. The deficiency of nitrogen (N) and phosphorus (P) among the nutrients is considered an important issue in soil fertility management programs. However, the ICRISAT-led watershed program across the Indian subcontinent provided the opportunity to diagnose and understand the widespread deficiencies of secondary nutrients such as sulfur (S) and micronutrients such as boron (B) and zinc (Zn) in the soils of rainfed areas. On-farm survey across various states in India, revealed that out of 1926 farmers' fields, 88 to 100% was deficient in available S, 72–100% in available B, and 67–100% in available Zn (Sahrawat *et al.*, 2007).

On-farm trials evaluated the response of crops to the application of S and micronutrients at the rate of 30 kg S, 0.5 kg B, and 10 kg Zn ha^{-1}. The results revealed 79% yield advantage in maize, 61% in castor, 51% in mung bean (green gram), and 28% in groundnut compared to the yield levels without the application of S and micronutrients (Table 10.15). Impressive economic gains due to improved soil fertility management to the extent of ₹5948 ha^{-1} in maize and ₹4333 ha^{-1} in groundnut were also reported from trials conducted under the ICRISAT-led watershed program in Andhra Pradesh (Table 10.16). Addition of micronutrients and S substantially increased productivity of crops and this resulted in increased RUE. The RUE of maize for grain yield under farmer nutrient inputs was 5.2 kg mm^{-1} compared to 9.2 kg mm^{-1} with S, B, and Zn application and farmer nutrient inputs; respective values in the same order of treatment were 1.6 kg mm^{-1} and 2.8 kg mm^{-1} for groundnut and 1.7 kg mm^{-1} and 2.9 kg mm^{-1} in mung bean (Table 10.17). However, addition of recommended dose of N and P along with S, B, and Zn in legumes further increased agricultural productivity, RUE, and incomes of the farmers.

Deshpande *et al.* (2007) investigated the effects of application of combination of mineral fertilizer (urea) and different organic sources (crop residues, sorghum waste, farmyard manure, and *Leucaena* loppings) on the productivity and WUE of sorghum

Table 10.16 Yield and economic returns in response to the application of nutrients in maize and groundnut in Andhra Pradesh, India[a]

	Maize		*Groundnut*	
Treatment	*Yield increase (%) over FP*	*Economic returns (₹ ha^{-1})*	*Yield increase (%) over FP*	*Economic returns (₹ ha^{-1})*
Farmers' practice (FP)	–	13931	–	12490
FP + S	26	17228	12	13660
FP + Zn	33	17479	27	14780
FP + B	33	18354	20	14850
FP + S + B + Zn	49	19429	48	16830
FP + S + B + Zn + N + P	75	21766	78	19520

[a]Source: Singh *et al.* (2009).

Table 10.17 Effect of micronutrient application on rainfall use efficiency in various field crops in Andhra Pradesh and Madhya Pradesh, India[a]

	Rainfall use efficiency (kg mm^{-1} ha^{-1})	
Crop	*Farmers' practice*	*Farmers' practice + micronutrients*
Andhra Pradesh		
Maize	5.2	9.2
Groundnut	1.6	2.8
Mung bean	1.7	2.9
Sorghum	1.7	3.7
Madhya Pradesh		
Soybean	1.4	2.7

[a]Source: Singh *et al.* (2009).

over five years. Higher consumptive use of water was recorded with the application of 50 kg N ha^{-1} through urea. Higher WUE was recorded with the application of 25 kg N ha^{-1} through crop residues +25 kg N ha^{-1} *Leucaena* loppings. The beneficial effects of organic material incorporation are attributed to improvements in the physical, chemical, and biological properties of the soil, e.g., infiltration rate, soil organic matter, and nutrient availability. Barros *et al.* (2007) reported that application of fertilizers (NPK) and lime to maize/cowpea intercrop on acid Acrisols of semi-arid northeastern Brazil increased biomass production and grain yield of the intercrop up to 400% and 550%, respectively. Improved crop growth with balanced nutrition reduced deep percolation and soil evaporation of rainfall, improved root development, and increased productive transpiration flow leading to overall increase in WUE. The omission of lime showed only minor effects on the evaporation and transpiration WUE. Nevertheless, the gross WUE was reduced up to 58% when lime was omitted and NPK applied at high inputs.

Table 10.18 Performance of improved varieties of finger millet and groundnut under different levels of management in Kolar and Tumkur districts, Karnataka during 2005 rainy season[a]

Finger millet			*Groundnut*		
	Yield (t ha^{-1})			*Yield (t ha^{-1})*	
Variety	*Farmers' practice*	*Improved management*	*Variety*	*Farmers' practice*	*Improved management*
Local	1.97	–	TMV 2 (local)	1.38	1.74
GPU 28	3.00	3.68	JL 24	1.92	2.80
MR 1	2.83	3.93	ICGV 91114	2.32	3.03
HR 911	2.90	3.66			
L 5	3.20	4.65			
Mean	3.00	4.00		1.88	2.52
Increase (%) over local variety	52	103		36	83

[a]Source: Singh *et al.* (2009).

10.7.2.3 Improved crop varieties and nutrient management

The adoption of improved varieties always generates significant field level impact on crop yield and stability. The yield advantage through the adoption of improved varieties has been recognized undoubtedly in farmer participatory trials across India under rainfed systems. Recent trials during the rainy season conducted across the Kolar and Tumkur districts of Karnataka, India revealed that mean yield advantage of 52% in finger millet was achieved with the use of high-yielding varieties like GPU 28, MR 1, HR 911, and L 5 under farmer nutrient inputs traditional management compared with use of local variety and farmer management (Table 10.18). These results showed that the efficient use of available resources by the improved varieties reflected in grain yields under given situations. However, yield advantage of 103% was reported in finger millet due to improved varieties under best-bet management practices (balanced nutrition including the application of Zn, B, and S and crop protection). Similarly, the use of improved groundnut variety ICGV 91114 resulted in pod yield of 2.32 t ha^{-1} under farmer management compared to the local variety under similar inputs. The yields of improved varieties further improved by 83% over the local variety with improved management that included balanced nutrient application (Singh *et al.*, 2009).

10.7.2.4 Water conservation practices and nutrient management

Rao *et al.* (2003) reported that the soils (Vertisols, Alfisols, Inceptisols, Entisols, and Aridisols) in rainfed areas are generally deficient in one or more nutrients. Balanced nutrition increased the amount of vegetative cover, which has a key role in reducing runoff and increasing the water infiltration. In view of the multi-nutrient deficiencies including those of major and micronutrients, the addition of optimum nutrients acts as an insurance against drought for the dryland crops. The supply of nutrients in the form of organic manures helps in retaining more moisture and increasing the water storage capacity and thereby increases water and nutrient use efficiency in drylands.

Combining the in-situ soil moisture conservation and balanced nutrient supply could boost the productivity levels in dryland agriculture (Rao *et al.*, 2003).

Degraded soils in the sub-Saharan zone are often unproductive because of nutrient imbalance and an inadequate water supply. Zougmoré *et al.* (2004) studied the effect of integrated local water and nutrient management practices on soil water balance, sorghum yield, and WUE on a Ferric Lixisol with 1.5% slope in the northern Sudanian zone of Burkina Faso. The treatments evaluated were soil and water conservation measures (stone rows, grass strips) and application of organic or mineral N-inputs (compost, manure, and urea) alone or in combination; and compared to a control treatment without N-input and soil and water conservation. The application of compost improved soil water storage in the rooting zone (0–80 cm) when combined with stone rows or grass strips and when the season had well-distributed rainfall. However, during an erratic rainy season, there was less soil water storage in the organic treatments than in the mineral source treatment. The authors concluded that the synergistic effect of water harvesting practices and the supply of organic or mineral resources increased WUE. It seems that an optimum combination of organic resources and fertilizers could improve the WUE (i.e., reduce runoff and drainage losses) and the productivity of Sahelian rainfed agriculture.

Oweis *et al.* (2003) has shown that substantial and sustainable improvements in water productivity can only be achieved through integrated farm-resources management. On-farm water-productive techniques coupled with improved irrigation management options, better crop selection and appropriate cultural practices, improved genetic make-up, and timely socioeconomic interventions help to achieve this objective. Conventional water management guidelines, designed to maximize yield per unit area, need to be revised for achieving maximum water productivity instead. A case study from Syria showed that when water is scarce, higher farm incomes can be obtained by maximizing water productivity than by maximizing land productivity.

10.7.2.5 Crop protection

Integrated pest management (IPM) is an effective and environmentally sensitive approach to pest management that relies on a combination of available pest suppression techniques to keep the pest populations below the economic thresholds. In other words, IPM is a sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks. New IPM products and methods are developed and extended to producers to maximize yields. On-farm trials on IPM were evaluated in the Bundi watershed, Rajasthan and Kothapally watershed in Andhra Pradesh and the results clearly demonstrated that IPM comprising use of suitable varieties, clean cultivation, scouting through pheromone traps, use of NPV (nuclear polyhedrosis virus) against lepidopteron pests, and installing bird perches resulted in yield advantage ranging from 18 to 56% for different crops. IPM practices also reduced the cost of pest management and provided stability in production as compared to farmers' practice of chemical control alone (Table 10.19). Beneficial effects on health and environment are additional bonus to the farmer and the society. Thus, IPM practices also contribute to increase in WUE through the increase in productivity per unit of rainfall or water used by the crops.

Table 10.19 Effect of IPM on the productivity of crops in Bundi and Kothapally watersheds in India[a]

Technology	*Crop*	*Cost of pest management (₹ ha^{-1})*	*Yield ($t\,ha^{-1}$)*	*Increase (%) in yield*
Bundi Watershed, Madhya Pradesh				
Farmers' practice	Green peas	1800	3.53	
IPM		1080	4.16	18
Kothapally Watershed, Andhra Pradesh				
Farmers' practice	Tomato	2057	2.45	
IPM		2637	3.82	56
Farmers' practice	Cotton		1.31	
IPM			1.64	25
Farmers' practice	Pigeonpea		0.52	
IPM			0.75	44
Farmers' practice	Chickpea		0.71	
IPM			0.84	18

[a]Source: GV Ranga Rao, ICRISAT, Personal communication.

10.7.2.6 Crop intensification (double cropping)

Evidence from long-term experiments at ICRISAT, Patancheru, India since 1976, demonstrated the virtuous cycle of persistent increase in yield and RUE through improved land, water, and nutrient management in rainfed agriculture. Improved systems of sorghum/pigeonpea intercrops produced higher mean grain yields ($5.1\,t\,ha^{-1}$ per yr) compared to, average yield of sole sorghum ($1.1\,t\,ha^{-1}$ per yr) in the traditional postrainy system (farmers' practice) where crops are grown on stored soil moisture with $5\,t\,ha^{-1}$ farmyard manure once in two years. The annual gain in grain yield in the improved system was $82\,kg\,ha^{-1}$ compared with $23\,kg\,ha^{-1}$ in the traditional system. The large gaps in yield and RUE show that a large potential of rainfed agriculture in terms of enhancing crop yields and RUE remains to be tapped (Figure 10.4). Moreover, the improved management system is still gaining in productivity as well as improved soil quality (physical, chemical, and biological parameters) along with increased carbon (C) sequestration of $330\,kg\,C\,ha^{-1}$ per year (Wani *et al.*, 2003a, 2009).

The practice of fallowing Vertisols and associated soils during the rainy season in Madhya Pradesh has decreased after the introduction of soybean. However, it is estimated that about 2.02 million ha of cultivable land is still kept fallow in Central India, where there is a vast potential for having crop during *kharif* (rainy season) (Wani *et al.*, 2002). A recent survey of farmers' fields revealed that the introduction of rainy season crop delays sowing of the postrainy season crop and frequent waterlogging of crops during the *kharif* season forces farmers to keep the cultivable lands fallow. Under such situations, ICRISAT research demonstrated the avoidance of waterlogging during the initial crop growth period on Vertisols by preparing the fields in BBF landform along with grassed waterways. Hence, timely sowing with short-duration soybean genotypes would pave the way for successful postrainy season crop where the moisture carrying capacity is sufficiently high to support successful performance of the postrainy season crop. Yield maximization and alternate crops can be tried in the postrainy season as there is assured moisture availability in the Vertisols of the region. On-station research

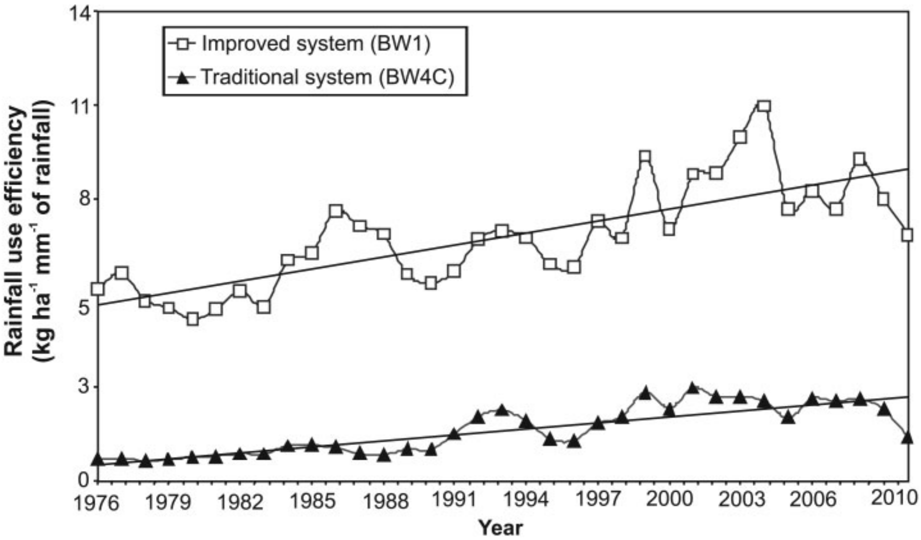

Figure 10.4 Three-year moving average of rainfall use efficiency in improved and traditional management systems during 1976–2010 at ICRISAT, Patancheru, India (Source: Recalculated from the data presented by Wani *et al.*, 2009)

was initiated with Indian Institute of Soil Science (IISS), Bhopal to address issues related to soil, water, and nutrient management practices for sustaining the productivity of soybean-based cropping systems in Madhya Pradesh. Then, the conceptual best-bet options were scaled-up in farmers' fields and yield advantages of 30 to 40% over the traditional system were recorded.

On-farm trials on soybean conducted by ICRISAT and partners to test improved land configuration (BBF system) and short-duration soybean varieties along with fertilizer application (including micronutrients) showed yield increase of 1300 to 2070 kg ha^{-1} compared to 790 to 1150 kg ha^{-1} in Guna, Vidisha, and Indore districts of Madhya Pradesh. The soybean varieties Samrat, MAUS 47, NRC 12, Pusa 16, NRC 37, JS 335, and PK 1024 were evaluated and the performance of JS 335 was better in Guna watershed than in Vidisha and Indore. Combination of improved technologies (land management, new varieties, and improved crop agronomy) increased crop yields (40–200%) and incomes (up to 100%) (Wani *et al.*, 2008).

10.7.2.7 Crop diversification with chickpea in rice fallows

It is estimated that about 11.4 million ha of rice fallows are available in India. The amount of soil moisture remaining in the postrainy season after harvest of the rice crop is usually adequate for raising a short-duration legume crop. Despite low yields of legumes grown after rice due to progressively increasing biophysical stresses, their low-cost of production and higher market prices often results in greater returns to the farmer. Thus the twin benefits of income and nutrition could be realized from legumes rather than from rice in spite of moderate yields of legumes. Introduction

Table 10.20 Productivity and water use efficiency of rice-chickpea system compared with rice-fallow system in the two districts of Chhatisgarh during 2008–09[a]

District	*Rainfall + irrigation (mm)*	*Cropping system*	*Total seed yield (kg ha^{-1})*	*Total net income (₹ ha^{-1})*	*WUE$_{(R+I)}$ (kg ha^{-1} mm^{-1})*	*WUE$_{(R+I)}$ (₹ ha^{-1} mm^{-1})*
Kanker	350	Rice-fallow	6090	55320	17.4	158
	390	Rice-chickpea	8510	84080	21.6	214
Bastar	350	Rice-fallow	3910	37300	11.1	106
	400	Rice-chickpea	5600	51480	13.9	127

[a]Source: Project Completion Report, Ministry of Water Resources, India.

of early maturing cool season chickpea in the rice fallows by addressing the crop establishment constraints will certainly improve cropping intensity and sustainability of the system. The main constraints to production of legumes in rice fallows are low P in the soil, poor plant establishment, low or absence of native Rhizobial population, root rot, and terminal drought. On-farm trials in eastern states of India on growing of early maturing chickpea in rice fallows with suitable best-bet management practices revealed that chickpea grain yields of 800-850 kg ha^{-1} can be obtained (Kumar Rao *et al.*, 2008). On-farm trials conducted in the two districts of Chhatisgarh state revealed that both productivity and WUE can be significantly increased by growing chickpea after rice. Because of high market value of chickpea, substantial improvements were recorded in the income of farmers per unit of water received by the crops (Table 10.20).

10.7.2.8 Contingent and dynamic cropping

Sadras *et al.* (2003) tested the hypothesis for the Mallee region of southeastern Australia that whole-farm profitability could be enhanced by the adoption of a dynamic cropping strategy shifting from a cereal-only, conservative strategy in dry years, to a more risky strategy involving both cereals and canola in wet years. To test this hypothesis, they used 40-years rainfall series to: (i) investigate rainfall features in 11 locations in the Mallee region, (ii) test the skill of simple rules to predict seasonal rainfall, as developed by local farmers, and (iii) calculate whole-farm profit for conservative, risky, and dynamic cropping strategies. Rainfall and profit were linked with a whole-farm model that estimates crop yield as a function of seasonal rainfall (i.e., rainfall from April to October) and WUE. Among locations, annual rainfall ranged from 259 to 358 mm. For each location, two types of seasons were defined: likely wet, when April rain was above the median and likely dry otherwise. The strength of the association between April and seasonal rain varied widely among sites; it was stronger in locations with more marked rainfall seasonality. Contrasting whole-farm profit responses to cropping strategies were found in locations with annual rainfall below or above a threshold around 300 mm. For wetter locations (annual rain above the threshold), the more risky cropping strategy including canola was generally more profitable than the more conservative strategy. For farms in drier areas, the cereal-based conservative strategy outperformed the more risky strategy in seasons predicted to be dry, but was less profitable in wet seasons. The dynamic cropping strategy had a substantial effect on extreme years, alleviating economic losses associated with the risky strategy in dry seasons, while being able to capture the benefits of more favorable seasons. Analysis of rainfall patterns, development of a rainfall forecasting procedure and quantification of whole-farm profit in response to cropping strategies, all highlighted the need for decision support tools that account for small-scale variation in rainfall characteristics.

10.7.3 Reducing soil evaporation

10.7.3.1 Mulches

In the semi-arid areas up to 50% of the rainfall is lost from the fields as non-productive soil evaporation. Converting some of that water to productive transpiration through evaporation management will increase water productivity in the arid, semi-arid, and dry subhumid regions. Options to reduce soil evaporation include dry planting, conservation agriculture, and mulching. Higher water productivity is achieved also by improving crop yields. When yields are low (between 1 and 2 t ha^{-1}), even small improvements in yield will generate large gains in water productivity. This non-linear relationship between water productivity and yield is due to the shading of the soil when the crop canopy becomes denser with higher yield, thus changing the ratio between productive transpiration and non-productive evaporation. Hence efforts to improve crop yields are beneficial from both water saving and income enhancing perspectives.

Dang TingHui *et al.* (2008) studied the effects of different straw and plastic film mulching modes and N fertilizer on yield of dryland wheat from 1998 to 2003. Under the dual mulching mode of plastic film and straw, grain yield increased by 12.11–17.65%, WUE increased by 7.2–30.8%, water content in the arable layer increased to 12–16%, and the nitrate N content in the arable layer increased to 4.70–10.17 mg kg^{-1}. The dual mulching mode of plastic film and straw significantly increased crop yield and WUE; thus nitrate leaching and accumulation in the soil profile was alleviated. Similar results on increase in productivity and WUE for maize have been reported (Mai ZiZhen *et al.*, 2007).

10.7.3.2 Microclimate modifications

The presence of windbreaks usually reduces ET by the crop. For this reason, the windbreak barrier is included among the agro-techniques specific for the dry farming systems. Campi *et al.* (2009) studied the effect of windbreaks on crop water requirements and yield on durum wheat growing in open field, in a typical Mediterranean environment. A windbreak *of Cupressus arizonica* (3 m in height) bordered at north of the experimental field. The analysis of the microclimatic observations showed that when wind blew from the North, the windbreak influenced the wind speed until the distance 12.7*H* (*H* is the windbreak height) and temperature increased in a distance of 4.7*H* from the barrier. On the basis of the soil water content, continuously measured by Time Domain Reflectometry (TDR) technique, ET was daily determined and season ET calculated. Windbreaks mitigated ET for a distance of 12.7 times the windbreak height. Outside this area, the ET was 16% higher than the ET measured near the windbreak belt ($<4.7H$). Yield performances changed according to the distance from the windbreak. Within the distance of 18 times the windbreak height, wheat production was higher than that obtained in the zone not influenced by the windbreak. Within

Table 10.21 Changes in water productivity from the adoption of sustainable agricultural practices in 144 projects by crop type (kg of produce per m^3 of water used)[a]

Crop	*Before intervention*	*After intervention*	*Gain*	*Increase (%)*
Irrigated agriculture				
Rice (18 projects)	1.03 (±0.52)	1.19 (±0.49)	0.16 (±0.16)	15.5
Cotton (8 projects)	0.17 (±0.10)	0.22 (±0.13)	0.05 (±0.05)	29.4
Rainfed agriculture				
Cereals (80 projects)	0.47 (±0.51)	0.80 (±0.81)	0.33 (±0.45)	70.2
Legumes (19 projects)	0.43 (±0.29)	0.87 (±0.68)	0.44 (±0.47)	102.3
Roots and tubers (14 projects)	2.79 (±2.72)	5.79 (±4.04)	3.00 (±2.43)	107.5

[a]Figures in parentheses are standard errors. Source: Pretty *et al.* (2006).

the protected area, wheat WUE (calculated as the ratio between yield and seasonal ET) attained the maximum value of 1.15; outside the area of windbreak protection, WUE was 0.70 kg m^{-3}. Since windbreaks reduce ET, farms of the Mediterranean environments should be redesigned in order to consider windbreaks as a possible issue of sustainability.

10.7.3.3 Land degradation, conservation agriculture, and water use efficiency

Land degradation reduces WUE at field and landscape scales and affects water availability, quality, and storage. Because of this strong link between land and water productivity, improving water management in agriculture requires that land degradation be mitigated or prevented. Bossio *et al.* (2010) reviewed the global experiences relating to land degradation and highlighted the important degradation processes (loss of soil organic matter, soil physical degradation, nutrient depletion, chemical degradation, soil erosion and sedimentation, and degradation of landscape functions) that are closely linked to water use and management. Investing in improved land management, such as resources-conserving technologies, can considerably improve on-farm WUE in both rainfed and irrigated agriculture (Table 10.21) (Bossio *et al.*, 2008). Resources-conserving technologies cover a broad range of systems which have the potential to improve WUE and water management in various ways. For example, soil management practices (such as zero till) to improve infiltration and soil water storage can boost WUE by an estimated 25–40%, while nutrient management can boost WUE by 15–25% (Hatfield *et al.*, 2001). Water productivity improvements can range from 70 to 100% in rainfed systems using resources-conserving technologies that enhance soil fertility and reduce water evaporation (Pretty *et al.*, 2006).

10.7.4 Crop breeding for increased water productivity

Improved crop varieties that produce more biomass and economic yield per unit of water uptake in water stressed environments would enhance the overall WUE of the production system. Gowda *et al.* (2009) reviewed genetic enhancement of dryland crops for improving crop water productivity. A combination of approaches has been employed to enhance the adaptation of crops to varying water availability environments. As a result of these approaches, several genetically enhanced products have been developed, some of which have reached the farmers' fields. Products of marker-assisted selection in pearl millet and maize have shown superior performance under severe drought conditions. There are several other successful plant breeding efforts that have improved plant water productivity (Dingkuhn *et al.*, 2006; Richards 2006).

10.8 PROMOTING ADOPTION OF TECHNOLOGIES

10.8.1 Enabling policies

In spite of greater investments in irrigated agriculture, crop yields have reached a plateau in most of the irrigated areas that had brought green revolution in Asia and other parts of the globe. The reasons for this are many and it is becoming difficult to enhance productivity and WUE with additional incremental input. Greater investments need to be made by governments in rainfed agriculture to close the yield gaps for efficient use of natural resources, particularly water. Greater national and local-level enabling policies are needed for the adoption of better practices by farmers. This would include sufficient and sustained access to natural resources (e.g., land and water), agricultural inputs, and credit to the farmers. Currently, these are insufficient and not at the desired level and need favorable policy changes in terms of enhancing their availability and easy access. For optimal water management, policies are needed to promote low-cost soil and water conservation measures and structures that have proved more useful and economical and more equitable than the large dams, which require heavy investments in the irrigated command area. In spite of increased water harvesting in rainfed areas, the groundwater levels in the rainfed areas are declining because of increased extraction of water by relatively rich farmers using bore wells. Water sharing mechanisms and water markets need to be developed for more efficient use of water.

10.8.2 Building institutions

To facilitate adoption of technologies and practices that enhance productivity and efficient use of resources, various institutions both at the local and state level need to be in place. First at the local level, all developmental approaches need to be farmer participatory, demand driven, and must provide tangible benefits to the farmers. Factors that promote collective action by the community, especially for the management and use of water resources, need to be promoted and practices that promote equity, equal partnership, shared vision, and trust should be encouraged. A consortium of institutions for technical guidance on the management of watersheds and water resources need to be fully operational. Institutional mechanisms at the district, state, and national level that promote adoption of technologies need to be more efficient in delivery to the farmers (Wani *et al.*, 2009). Water management institutions at the local level for participatory groundwater management need to be supported and guided for more efficient use of water resources. Various institutional structures such as market, finance, and risk management need to be in place for transaction of agricultural inputs and outputs by farmers and to cover the risks associated with farming in rainfed areas.

10.8.3 Raising awareness and capacity building

Farming communities have traditional knowledge, which they have been applying over years for the management and use of natural resources, while the scientific community and the government implementing agencies are more equipped with the new knowledge gathered through scientific developments. In many situations the traditional knowledge needs to be blended with new developments for upgrading the practices for sustainable agricultural development. There is a need to empower communities and village-level institutions for adopting new technologies that enhance productivity and efficient use of natural resources that enhance productivity and a strong social and human capital will enhance sustainability of the developmental programs. Often the poor and women take care of agriculture when the men migrate for alternative livelihood. Their participation in water user groups and capacity building could prove more meaningful and effective in management of natural resources. As the extension services are not able to cope with the growing needs of the farmers, new ICT (information and communications technology) based knowledge transfer systems need to be put in place at village levels for serving the needs of farmers (Sreedevi and Wani 2009).

10.9 SUMMARY AND CONCLUSIONS

Globally, rainfed agriculture is very important as it generates 58% of the world's staples; and most food of the poor communities is produced in the rainfed areas of developing countries. Underdevelopment, rapid population increase, land degradation, climate uncertainty, water scarcity, and unfavorable government policies are the major bottlenecks to achieving higher agricultural production and improved rural livelihoods. The farming community is facing water crisis due to excessive groundwater withdrawal and climate change with little scope for expansion of large-scale irrigation systems. Therefore, the available water resources need to be used more efficiently not only for increasing crop production, but also to build resilience for coping with the climate related risks and uncertainties. An assessment of potential yields and water use by crops have indicated that there are large gaps in productivity and WUE of rainfed crops in different agroclimatic regions. The potential to increase productivity and WUE of crops increases from the arid to subhumid agroclimate where more surplus water is available for increasing total productivity per unit of land. Therefore, an IWRM approach is needed, which involves efficient management of all the components of water cycle for enhancing crop productivity to meet the current and future food security of the nations. A large number of rainwater conservation and management and productivity enhancing technologies have been successfully demonstrated by various workers at research stations and under on-farm situations in farmers' fields. The challenge is how to further scale-up the adaptation and adoption of these technologies by large number of farmers in different agroclimatic zones of rainfed areas to improve productivity of water. Climate change will have both direct and indirect adverse impact on productivity and WUE of production systems. The currently available technologies will have to be further fine tuned or newer ones may have to be developed to make the production systems more sustainable and resilient to the adverse impacts of climate change. Production is also limited by various non-water factors such as labor shortage, insecure land ownership, inadequate access to capital for investments, and limited skills and abilities. Therefore, for increased adoption of crop productivity and WUE, enhancing technologies by rural communities, appropriate institutional and policy support, and increased awareness and capacity building of stakeholders at different levels are essential to achieve the overall goal of food security and resilience in the rainfed areas.

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