Soil Science

SOIL WATER AND AGRONOMIC PRODUCTIVITY

Crop water use can be increased by management of surface runoff, groundwater, irrigation, and soil water. Technological innovations to enhance availability of water for agricultural crops depend on soil and site-specific conditions. Devoted to the principles and practices of enhancing water use efficiency, **Soil Water and Agronomic Productivity** addresses current problems associated with water supplies required for agricultural purposes and food production.

Written for professionals and students in agricultural fields, the book focuses on innovative technologies for improving soil water availability, enhancing water use efficiency, and using productive irrigation systems. It also presents techniques to conserve water in the root zone as well as remote sensing techniques to assess soil water regime and predict drought on a regional scale.

Soil water management is crucial to reducing the vulnerability to agronomic drought. There are numerous examples of aquifers that have been severely depleted by misuse and mismanagement. **Soil Water and Agronomic Productivity** explains the factors and causes of the mismanagement of soil water and proposes options for sustainable and efficient use of scarce water resources. Meeting the global food demand will require careful worldwide management of soil and water resources, and this can only be done by sharing information and knowledge.

Part of the Advances in Soil Science Series

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SOIL WATER AND AGRONOMIC PRODUCTIVITY

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Stewart

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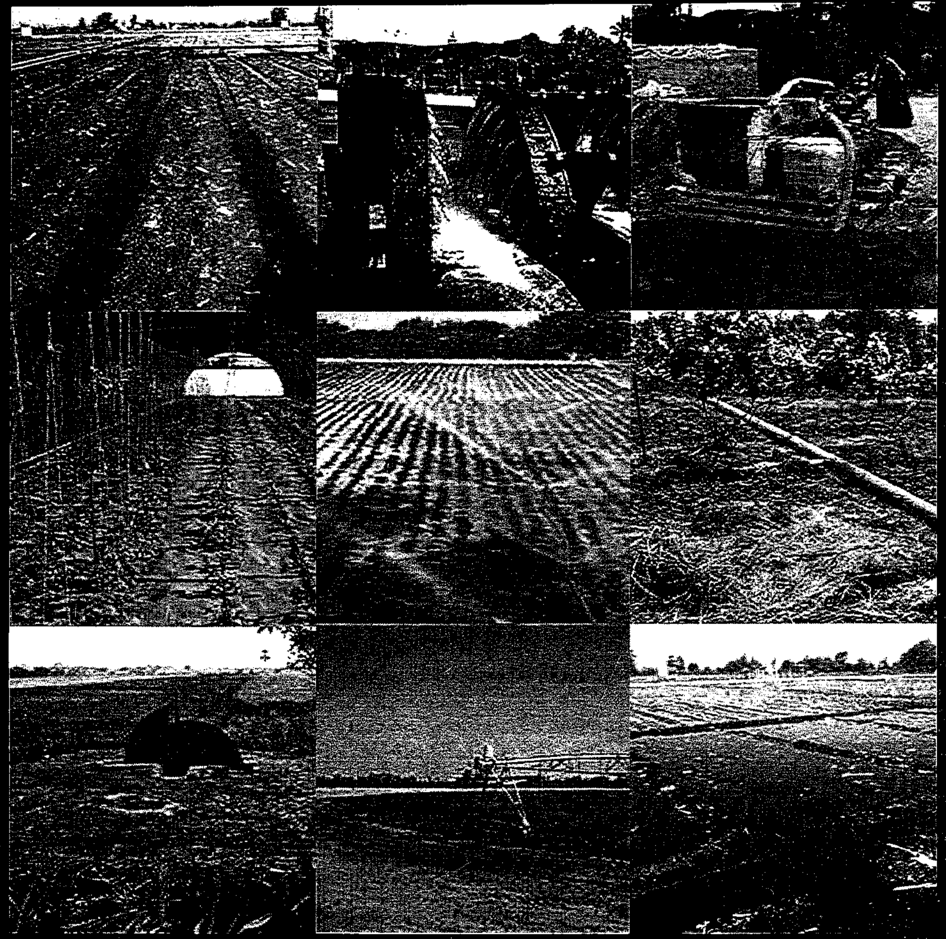
Advances in Soil Science

SOIL WATER AND AGRONOMIC PRODUCTIVITY



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13 Sustainable Management of Scarce Water Resources in Tropical Rainfed Agriculture

Suhas P. Wani, Kaushal K. Garg,
Anil Kumar Singh, and Johan Rockström

CONTENTS

13.1 ACHIEVING GLOBAL FOOD SECURITY IS A CHALLENGE

Ensuring global food security for the ever-growing population that will cross 9 billion by 2050 and reducing poverty are challenging tasks. Growing per capita income in the emerging giant economies such as Brazil, Russia, India, and China (BRIC) implies increased additional pressure on global food production due to changing food habits. The increased food production has to come from the available and limited water and land resources, which are finite. The quantity of neither available water nor land has increased since 1950, but the availability of water and land per capita has declined significantly due to increase in global human population. For example, in India, per capita water availability has decreased from 5177 m^3 in 1951 to 1820 m^3 in 2001 due to increase in population from 361 million in 1951 to 1.02 billion in 2001, which is expected to rise to 1.39 billion by 2025 and 1.64 billion by 2050 with associated decrease in per capita water availability of 1341 m^3 by 2025 and 1140 m^3 by 2050, respectively. Distribution of water and land varies differently in different countries and regions in the world as also the current population and anticipated growth, which is likely to be more in developing countries. In 2009, more than 1 billion people went undernourished; it is not because of shortage of food (availability), but because people are too poor to buy (accessibility). Although the percentage of hungry people in the developing world had been dropping for decades (Figure 13.1), the absolute number of hungry people worldwide has barely dipped. The recent food price crises in 2008 reversed the decades of gains (*Nature* 2010). In this chapter, we analyze the current status of agricultural water use in the tropical rainfed areas, assess the potential, and propose a new paradigm to manage agricultural water efficiently through a holistic watershed management approach and operationalize the integrated water resource management (IWRM) strategy for harnessing the untapped potential of rainfed agriculture in the tropics to increase food production and improve the livelihoods of people with finite and scarce water resource.

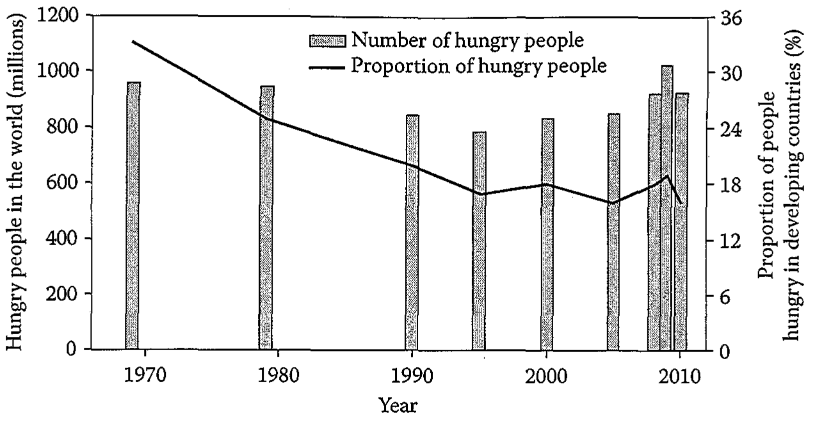

FIGURE 13.1 Total number of hungry people in the world and the proportion in developing countries. (Data from FAOSTAT. http://hungerreport.org/2011/data/hunger.)

13.2 FINITE AND SCARCE FRESHWATER RESOURCES

Water, a natural resource, is a finite one and keeps circulating through the hydrological cycle of evaporation, transpiration, and precipitation mainly driven by various climatic and land management factors (Falkenmark 1997). The total water on earth is 1385.5 million km^3 (Shiklomanov 1993), out of which 97.3% is salt water in oceans. Fresh water constitutes only 2.7% of total global water resource and is the lifeline of the biosphere where forests, woodlands, wetlands, grasslands, and croplands are the major biomes (Postel et al. 1996; Rockström et al. 1999). Rockström et al. (1999) reported that about 35% of annual precipitation (110,305 km^3) received on the earth's surface returns to the oceans as surface runoff (38,230 km^3) while the remaining 65% is converted into water vapor flow. Moreover, major terrestrial biomes, that is, forests, woodlands, wetlands, grasslands, and croplands, together consume almost 98% of the global green water flow (Figure 13.2) and generate essential ecosystem services (Rockström et al. 1999; Rockström and Gordon 2001). Freshwater availability for producing a balanced food diet (i.e., 3000 Kcal/person/day) under the present conditions concomitant with increasing population pressure is an important concern. Figure 13.2 shows that on an average, 6,700 and 15,100 km^3/year of consumptive fresh water is used by croplands and grasslands, which generate food and animal proteins for feeding humanity, respectively (Rockström and Gordon 2001). This quantity is 30% of the total green water flux on the earth.

13.2.1 Green and Blue Water

Water resources are classified into green water and blue water resources (Falkenmark 1995); rainfall is partitioned into blue and green water resources through an important hydrological process (Figure 13.3). Green water is the large fraction of precipitation, which is held in the soil and available for plants' consumption on-site and it returns to the atmosphere through the process of evapotranspiration (ET). A fraction of green water that is consumed by plants is referred to as transpiration and the amount that returns to the atmosphere directly from water bodies and soil surface is labeled as evaporation. Blue water is the portion of precipitation that enters into streams and lakes and also recharges groundwater reserves. Human beings can directly consume blue water for their domestic and industrial uses and also for food production off-site (away from the area where it originates).

Freshwater consumption for major biomes assessed by Rost et al. (2008), however, is comparable with the estimates by Rockström et al. (1999), but this value for grasslands is dissimilar (8258 km^3/year by Rost et al. 2008 compared to 15,100 km^3/year by Rockström et al. 1999) probably due to difference in the methodologies adopted.

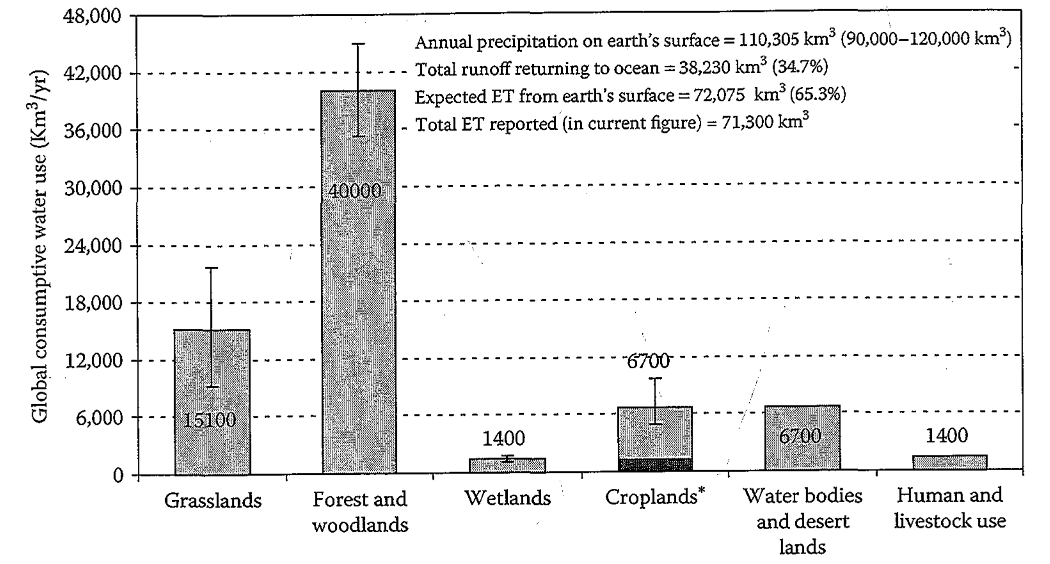

FIGURE 13.2 Global annual consumptive water use of major terrestrial biomes. (Data from Rockström, J., Gordon, L., Folke, C., et al., *Conservation Ecology*, 3(2), 5, 1999; Rockström, J. and Gordon, L., *Physics and Chemistry of the Earth*, 8(26)(11–12), 843–851, 2001.) *Consumptive water used by croplands is partitioned as (1) ET for productive use (upper portion) and (2) ET in noneconomic vegetation including weeds and vegetation in open drainage ditches, green enclosures, and wind breaks (lower portion).

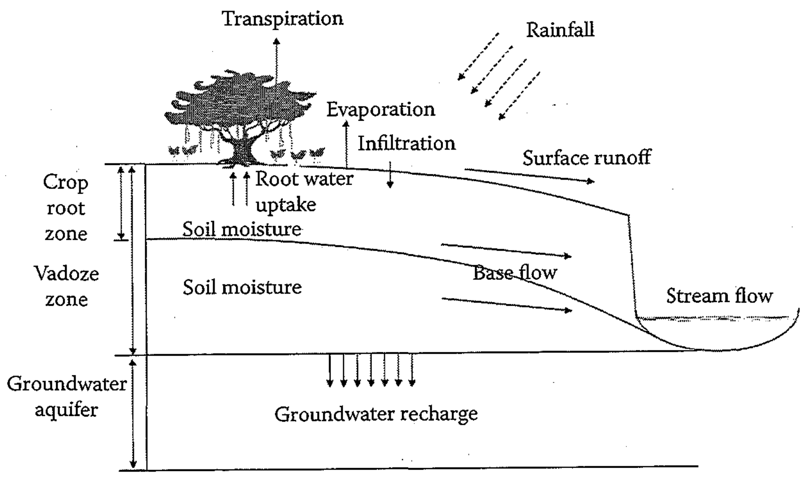

FIGURE 13.3 Conceptual representation of the hydrological cycle and different hydrological components.

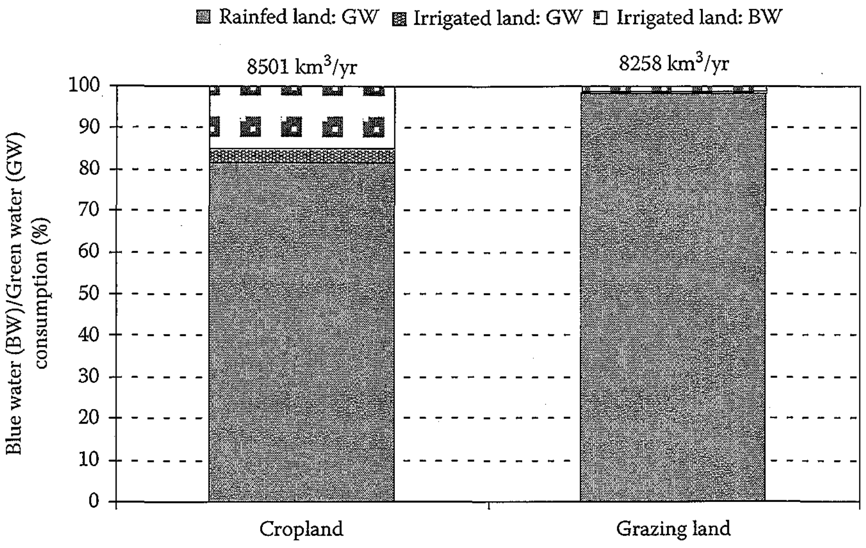

FIGURE 13.4 Blue and green water contribution of consumptive use in cropland and grazing land. (Data from Rost, S., Gerten, D., Bondeau, A., Luncht, W., Rohwer, J., Schaphoff, S., et al., *Water Resources Research*, 44, W09405, doi:10.1029/2007WR006331, 2008.)

Figure 13.4 shows consumptive use of blue and green water from croplands and grasslands (Rost et al. 2008), and the share of green water (adding part one and two) is about 85% of total consumptive freshwater use in cropland and 98% in grassland in the entire globe. Although the contribution of green water in generating global food production is significantly high (Rockström et al. 1999; Rost et al. 2008; Hoff et al. 2010), traditionally, emphasis has been given on augmenting blue water resources (Molden et al. 2007; Falkenmark and Molden 2008; Sulser et al. 2010), and green water potential has not been harnessed properly (Falkenmark et al. 2009; Wani et al. 2009a, 2011a). Large dams/reservoirs were constructed on every important river basin for harvesting river water (Falkenmark and Molden 2008). Figure 13.5 shows the global blue water withdrawal, its consumptive use for domestic and irrigation purpose, and the expansion of cropland and pasture land since 1900. It is clear from the figure that total blue water withdrawal at present has increased by 350% (3800 km^3/year) compared with that in the 1940s, and there is not much scope left to harvest blue water further (Scanlon et al. 2007). With increasing food demand, huge land areas were converted from forest/woodlands to croplands and grasslands, which resulted in reduction in ET by 4% (equivalent to 3000 km^3/year) globally compared with its original native stage. On the other

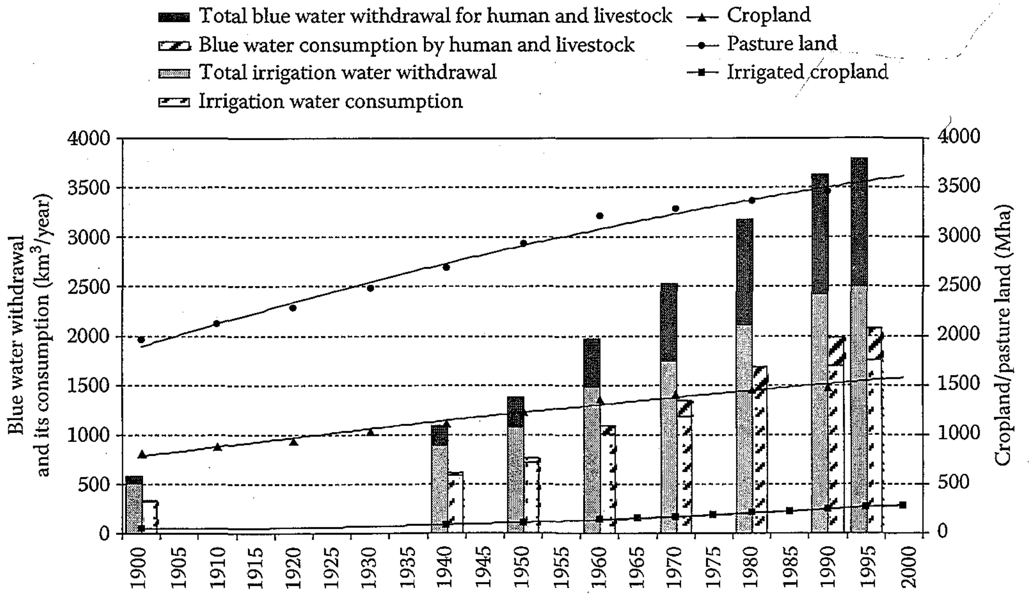

FIGURE 13.5 Total blue water withdrawal for human/livestock and irrigation purpose and its consumptive use since 1900 onward; Expansion of total cropland, pasture land and irrigated land globally since 1900 onward. (Data from Scanlon, B.R., Jolly, I., Sophocleous, M., et al., *Water Resource Research*, 43, W03437, doi:10.1029/2006WR005486, 2007.)

hand, developed water resource projects have enhanced vapor flow by 2600 km^3/year in subsequent years (Gordon et al. 2005). However, the net change in global vapor flows is negligible, but differential spatial distribution of deforestation and irrigation has led to change in ecosystems and rainfall pattern at the local, regional, and global scales (Gordon et al. 2005).

13.2.2 ZOOMING IN ON FRESHWATER RESOURCES IN INDIA

Out of the annual average precipitation of 4000 km^3 over the country, 1120 km^3 is partitioned as blue water (690 and 430 km^3 surface and groundwater resources, respectively) and the remaining 2880 km^3 is available as green water. Land use in India in 2001–2002 shows that 49% of total geographical area is cultivable, 22% area is under forest, 20% area is under wasteland and fallow category, and 9% land is for other uses and not available for cultivation. At present, a total of 142 mha (43% of total geographical area) is the net cultivated area under agricultural use; within that, 40% is irrigated and 60% used for rainfed farming.

From 1950 to 2000, the gross cultivated area (rainfed and irrigated) has increased from 130 mha to 190 mha (Figure 13.6a), whereas the net sown area has remained virtually constant for the last four decades. The cropping intensity of the current production system is 135%. Irrigated area has increased from 17% to 40% (0.8% expansion per year) in a span of 50 years. Within irrigated agriculture, the area irrigated by groundwater is 65% and surface water is 35%.

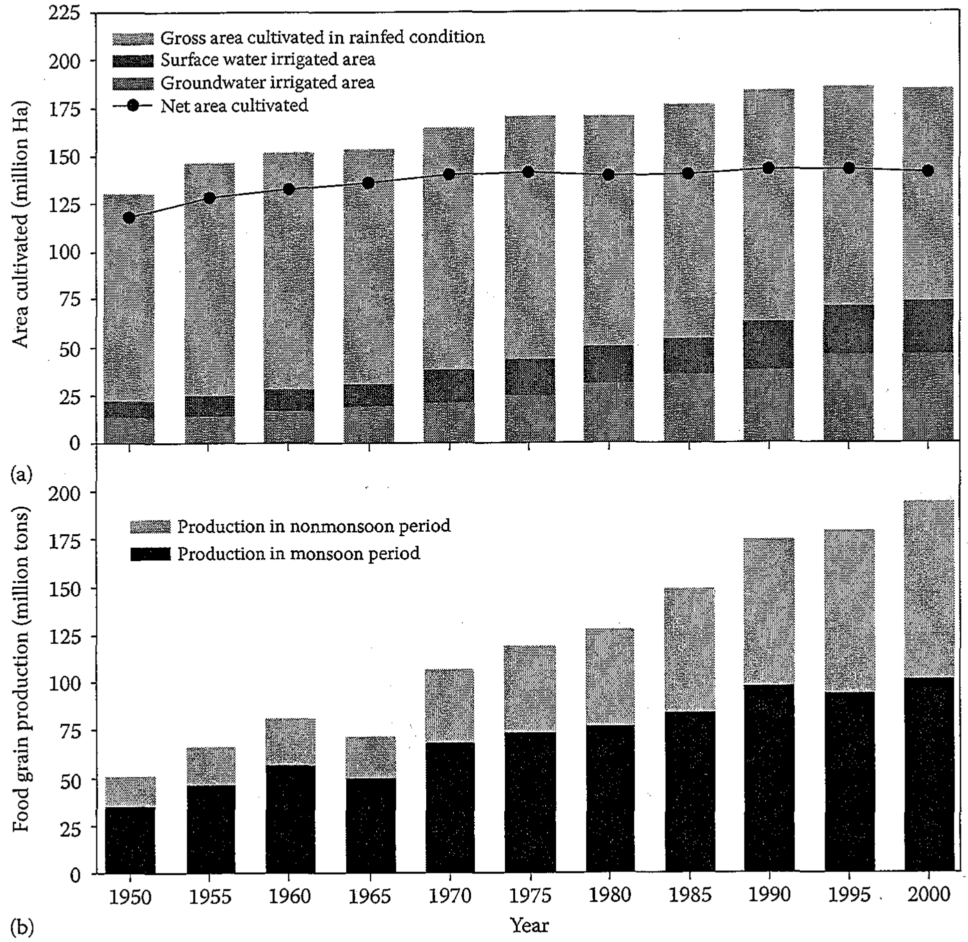

FIGURE 13.6 (a) Gross area cultivated in rainfed and irrigated (groundwater and surface water-irrigated area) croplands and net cultivated area in India; and (b) total food production (during monsoon and postmonsoon period) in India. (Data from Centre Water Commission, *Hand Book of Water Resources Statistics*, 2005. http://www.cwc.nic.in/main/webpages/publications.html.)

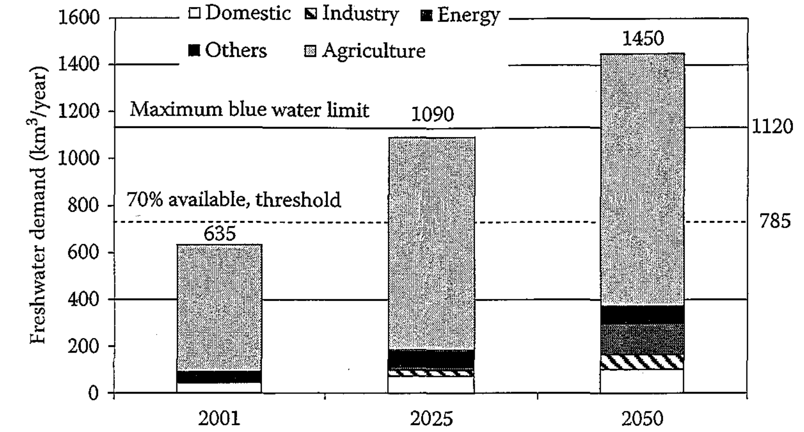

FIGURE 13.7 Present and anticipated future freshwater demand for food production and other uses in India; solid and dashed horizontal lines show the maximum and sustainable (70% of maximum) blue water thresholds. This scenario assumes that water productivity from rainfed and irrigated agriculture will remain same in the future as the current production system. *Note*: Consumptive green water use from croplands has not been reported in this figure. (Data from Centre Water Commission, *Hand Book of Water Resources Statistics*, 2005. http://www.cwc.nic.in/main/webpages/publications.html.)

Food grain production in India during monsoonal and nonmonsoonal periods is shown in Figure 13.6b. The green revolution in the 1970s significantly increased crop productivity and total grain production, which resulted in food self-sufficiency. Moreover, development of canal command areas (major and minor irrigation projects), village electrification, development of irrigation technology, and infrastructure all together converted substantial fraction of rainfed land into irrigated agriculture (Figure 13.6a). Available fresh water, however, is sufficient enough to meet the current food demand in the country but it will fall severely short with the increasing population pressure in the future. Figure 13.7 shows anticipated freshwater demand (in different sectors: domestic, agriculture, industry, energy, and others) in 2025 and 2050 and also explains maximum and sustainable blue water thresholds. This analysis assumes that water productivity (WP) of rainfed and irrigated agriculture in the future will remain the same as of the current production system. Under this scenario, all blue water will have to be harvested (Table 13.1) and diverted for human consumption by 2025, which may jeopardize social fabric in the society, environment, and ecosystems. Moreover, freshwater demand in 2050 will be much higher than maximum available blue water resources, clearly suggesting that blue water resource alone will not be sufficient to satisfy future water needs in India. The vast untapped potential of rainfed agriculture will have to be harnessed to meet future food and water demands of the country (Wani et al. 2003a, 2008, 2009a, 2011a; Rockström et al. 2007, 2010; Sharma et al. 2010).

13.2.3 COMPETING DEMANDS FOR LIMITED AVAILABLE WATER FROM DIFFERENT SECTORS

Water scarcity is particularly acute in many developing countries where there is an urgent need to eradicate poverty and improve quality of life for people to exist. River flows are declining with increasing water resources development, which has led to serious transboundary issues and conflicts among different stakeholders in addition to a growing concern over the social and environmental impacts (Landell-Mills and Porras 2002; Bunn and Arthington 2002). Moreover, great uncertainty is arising on future water availability due to upcoming climate changes (IPCC 2007). Extreme events such as flash floods or longer dry spells, more number of dry or wet years, change in crop

TABLE 13.1
Surface and Groundwater Potential: Current and Future Utilization in India

Surface Water Resources	**Fresh Water (km^3)**
Utilizable average surface water (per year)	690
Reservoir storage capacity	213
Projects under construction	76
Projects for further consideration	108
Groundwater Resources	
Replenishable groundwater	430
Available for agricultural use	360
Net draft at present	115

Source: Data from Centre Water Commission, *Hand Book of Water Resources Statistics*, 2005. http://www.cwc.nic.in/main/webpages/publications.html.

water demand, temperature change, and pest/disease infestation are the various characteristics driven by the climate change phenomenon.

As stated earlier, water availability for croplands and grasslands is becoming less with increasing population pressure and changing food habits (Rockström et al. 1999, 2009). Figure 13.8 shows the present and anticipated future food demands (Figure 13.8a) in developing and developed countries and corresponding total freshwater requirements (Figure 13.8b for developing countries and Figure 13.8c for the entire globe) if the current trend of WP continues in the future as well (Rockström et al. 2007). It is anticipated that total food demand in 2050 will be approximately 11,200 million tons, out of which 9300 million tons of food will be required for developing countries (de Fraiture et al. 2007; Rockström et al. 2007; Khan and Hanjra 2009; Hanjra and Qureshi 2010).

Blue water in most of the river basins (except sub-Saharan Africa [SSA]) has already been diverted for domestic/industrial use and also in irrigated agriculture for food production (Figure 13.5), with little scope left for further harvest. There are two alternatives for meeting increasing food demand: (i) improvement in WP with existing croplands (both rainfed and irrigated) and grasslands and (ii) expansion in agriculture areas by clearing some fraction of forest/woodlands and wetlands into croplands; or a combination of these two. Several examples/studies show that change in land use from forestlands to crop/grasslands, however, increased food production but developed imbalance in the traditional terrestrial ecosystem and feedback mechanism, with the loss of ecosystem resilience and also various other ecosystem services. This also led to climate change from local to regional/global level and reduction in overall water availability (Gordon et al. 2005; Hoff et al. 2010). For example, the mass clearing of *Eucalyptus mallee* forest to croplands and pasture lands in Australia in the late 1800s and early 1900s initially increased the groundwater table, which subsequently created waterlogging and soil salinization problems over the landscape (Scanlon et al. 2007). Similarly, conversion of natural savannas into millet-growing rainfed land in Niger, Africa, enhanced surface runoff, resulting in soil loss and primary gully formations (Leduc et al. 2001; Massuel et al. 2006; Scanlon et al. 2007).

13.3 UNDERSTANDING WATER SCARCITY

Assessment of the amount of renewable surface and groundwater per capita (i.e., the so-called blue water) suggests that water stress is increasing in a number of countries, as we understand

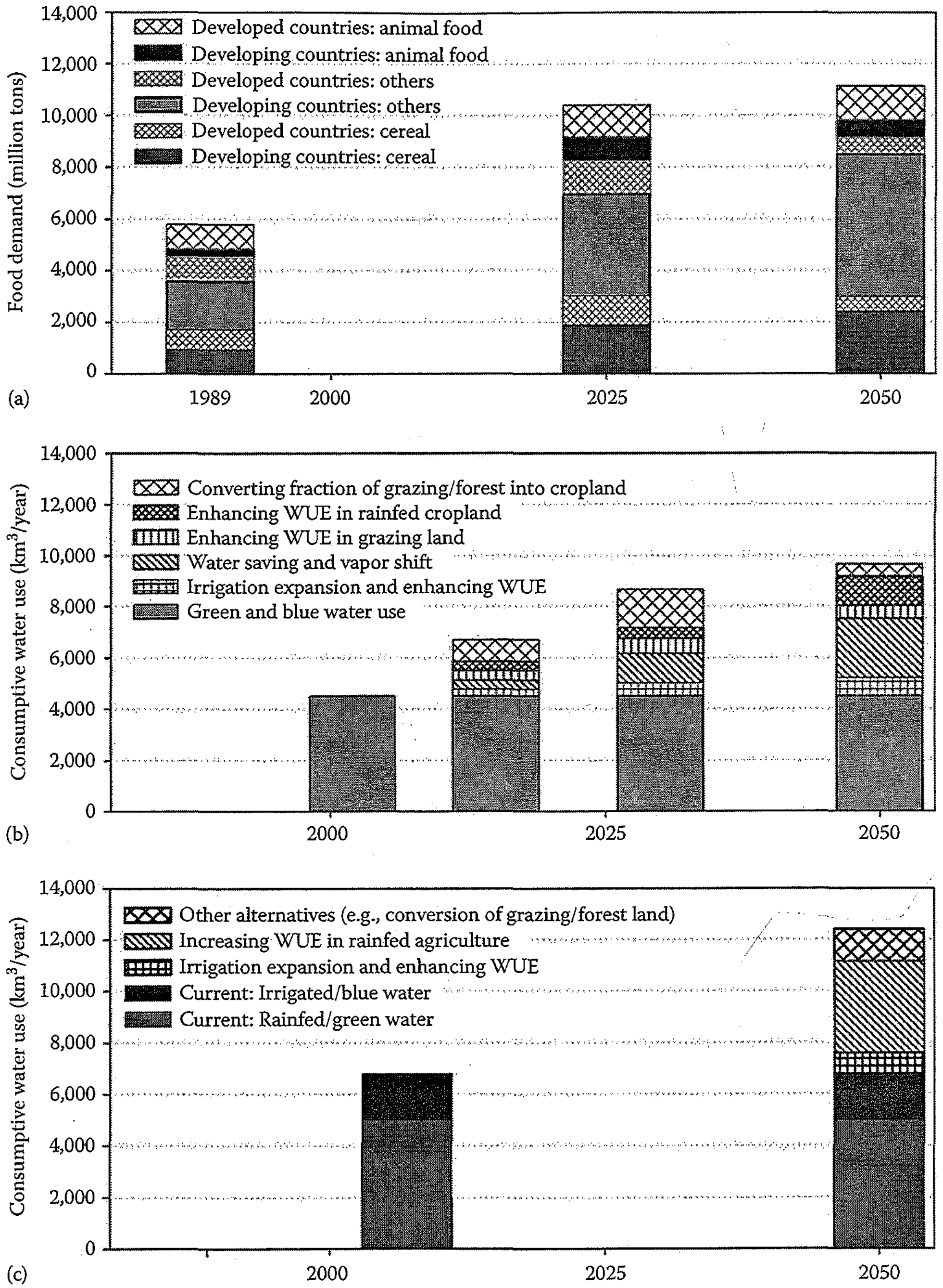

FIGURE 13.8 (a) Present and anticipated future global food demand; present and future fresh water required for food production and possible source to fill up demand gap (b) in developing countries; and (c) both in developing and developed countries. (Data from Rockström, J., Hatibu, N., Oweis, T., et al., In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, pp. 315–348, Earthscan, London and International Water Management Institute (IWMI), Colombo, Sri Lanka, 2007; de Fraiture, C., Wichelns, D., Rockström, J., et al., In *Comprehensive Assessment of Water Management in Agriculture, Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, pp. 91–145, International Water Management Institute, Colombo, Sri Lanka and Earthscan, London, UK, 2007; Khan, S. and Hanjra, M.A., *Food Policy*, 34(2), 130–140, 2009; Hanjra, M.A. and Qureshi, M.E., *Food Policy* 35, 365–377, 2010.)

conventionally. However, water scarcity is a relative concept and water is not equally scarce in all parts of the world. As Figure 13.9a illustrates, South Asia (SA), East Asia (EA), and the Middle East North Africa (MENA) regions are the worst affected in terms of blue water scarcity. However, this picture may be misleading because these water quantities only include blue water and full resource, notably rainwater "green water," that is, soil moisture used in rainfed cropping and natural vegetation is not included. Further, the average amount of water per capita in each pixel could obscure large differences in actual access to a reliable water source. In a recent assessment that included both green and blue water resources, the level of water scarcity changed significantly for many countries (Figure 13.9b) and suggested that large opportunities are still possible in the management of rainfed areas, that is, the green water resources in the landscape (Rockström et al. 2009; Wani et al. 2009a, 2011b). The current global population that has blue water stress is estimated to be 3.17 billion and is expected to reach 6.5 billion in 2050. If both green and blue water are considered, the number currently experiencing absolute water stress is a fraction of this (0.27 billion) and will only marginally exceed today's blue water stress in 2050.

Absolute water stress is found most notably in arid and semiarid regions with high population densities such as parts of India, China, and the MENA region. The MENA region is increasingly unable to produce the food required locally due to increasing water stress from a combination of population increase, economic development, and climate change and will have to rely more and more on food (and virtual water) imports.

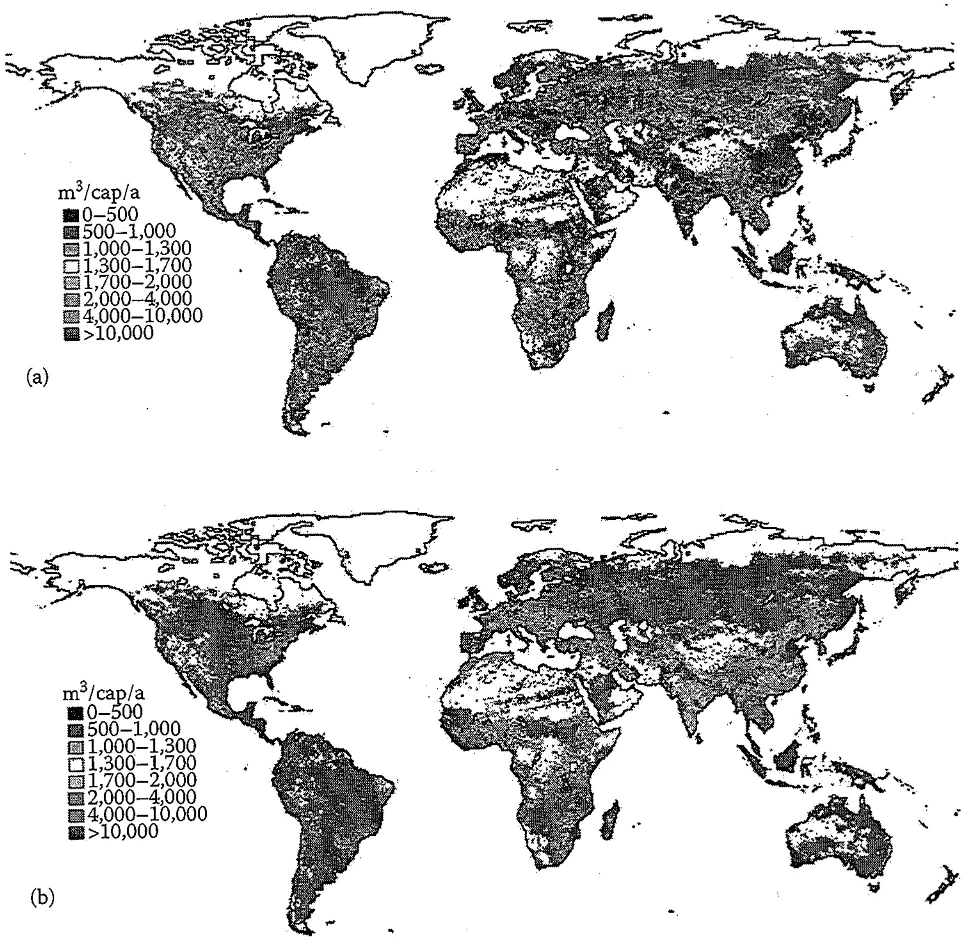

FIGURE 13.9 (a) Renewable liquid freshwater (blue) stress per capita (m^3/cap/a) using LPJ dynamic modeling year 2000. (b) Renewable rainfall (green and blue) water stress per capita (m^3/cap/a) using LPJ dynamic modeling year 2000. (From Rockström, J., Falkenmark, M., Karlberg, L., et al., *Water Resources Research*, 45, W00A12, doi:10.1029/2007WR006767, 2009.)

Among the regions that are conventionally (blue) water-scarce but still have sufficient green and blue water to meet the water demand for food production are large parts of SSA, India, and China. If green water (on current agricultural land) for food production is included, per capita water availability in countries such as Uganda, Ethiopia, Eritrea, Morocco, and Algeria more than doubles or triples. Moreover, low ratios of transpiration to evapotranspiration (T/ET) in countries such as Bangladesh, Pakistan, India, and China indicate high potential for increasing WP through vapor shift (Rockström et al. 2009).

Considering the vast rainfed areas (1.25 billion hectares) covering 80% of cultivated land and 85% of consumptive use of fresh water in agricultural land, agricultural water management is larger than irrigation (blue water). There is an urgent need to make all the stakeholders understand the need to consider large quantities of available green water globally and the potential to enhance water-use efficiency (WUE) for food production. Not only is water availability for food production restricted to blue water but green water also needs to be brought into the ambit for management and harnessing the potential.

Given the increasing pressures on water resources and the increasing demands for food, fiber, and biofuel crops for energy, the world must succeed in producing more food with less water. Hence, it is essential to increase WP in humid, semiarid, and arid regions. Some describe the goal as increasing the "crop per drop" (more crops per drop) or the "dollars per drop" (more income per drop) produced in agriculture. Regardless of the metric, it is essential to increase the productivity of water and other inputs in agriculture. Success on this front will generate greater agricultural output, while enhancing water availability in other sectors and contributing to environmental quality. There are several field and simulation studies showing huge untapped potential of rainfed and irrigated areas (Wani et al. 2003a, 2008, 2009a, 2011b; Rockström et al. 2007; Fisher et al. 2009; Kijne et al. 2009; Sahrawat et al. 2010a). The main reasons for poor WUE in rainfed areas are land degradation, water scarcity, lack of knowledge among farmers, low and inappropriate input use, and climatic variability (Barron et al. 2003; Kijne et al. 2003; Molden et al. 2007; Wani et al. 2003a, 2007, 2009a; Sharma et al. 2010). Water availability in irrigated areas, especially in canal command areas, is good but poor water management, lack of institutional arrangements, and faulty government policies (e.g., subsidy on canal water use and free electricity for groundwater pumping) are the main reasons for poor WUE (Molden et al. 2007). Overdrafting and more water inputs are the common practices in irrigated areas (e.g., in India), which leads to waterlogging and soil salinity problem (Khare et al. 2007; Shah et al. 2007) and declining productive status of the landscape subsequently (Manjunatha et al. 2004; Rajak et al. 2006).

13.3.1 WATER SCARCITY AND POVERTY IN THE TROPICAL REGIONS

There is a correlation between poverty, hunger, and water stress (Falkenmark 1986). A recent study by Rockström and Karlberg (2009) mapped hot spots of poverty in SSA, SA, and EA for bridging the yield gaps in rainfed areas where agriculture is the principal source of economy and livelihood of millions of people in developing countries. Poor investment/capacity, poor financial structures, and poor extension support are the major reasons keeping rainfed farming at subsistence level. Furthermore, landholdings are becoming smaller, and consequently land share and livelihood opportunities are reducing (Wani et al. 2011b). The UN Millennium Development Project has identified the "hot spot" countries in the world suffering from the largest dominance of malnourishment. These countries coincide closely with those located in the semiarid and dry subhumid hydroclimates in the world, that is, savannahs and steppe ecosystems, where rainfed agriculture is the dominating source of food and where water constitutes a key limiting factor to crop growth (SEI 2005). Following this, we strongly make an evidence-based case for harnessing the full potential of vast rainfed areas through operationalizing the IWRM framework for enhancing crop yields through increasing WP.

13.4 CHALLENGES AND OPPORTUNITIES FOR WATER MANAGEMENT IN RAINFED AGRICULTURE

For obvious reasons, water is the primary limiting factor in dryland agriculture (Falkenmark and Rockström 2008). Rainfall in dry land areas is characterized by erratic and nonuniform distribution, which results in frequent dry spells at different time periods during the monsoon. Barron et al. (2003) studied dry spell occurrence in semiarid locations in Kenya and Tanzania and found that meteorological dry spells of >10 days occurred in 70% of seasons during the flowering stage of the crop (maize), which is very sensitive to water stress. Regions with similar seasonal rainfall can experience different dry spell occurrence. In the semiarid Nandavaram watershed, Andhra Pradesh, India, with approximately 650 mm of rainfall, there is a high risk of dry spell occurrence (>40% risk) during the vegetative and flowering stages of the crop, compared with semiarid Xiaoxingcun, southern China, receiving similar rainfall, but with only a 20% risk of early season dry spells (Rao et al. 2007).

For achieving better crop growth and yield, a certain amount of water is essentially required to meet plant metabolic and evaporative demands (Stewart et al. 1975). There exists a direct relationship between consumptive water use (ET) and crop growth/yield. Rockström et al. (2007) described that if all the green water captured in the root zone is utilized fully by crop, a yield of 3 t/ha in rainfed agriculture is achievable. If water that is lost as deep percolation and surface runoff is also made available to crop, then production level would reach 5 t/ha and further up to 7.5 t/ha. All the above such conditions assume that nutrient availability for plant is nonlimiting. In reality, only a small fraction of rainfall is used by the plant (through transpiration) while the rest is channelized through nonproductive use and lost from crop production system. A water stress situation, especially during critical growth stages, reduces crop yield and may even seriously damage the entire crop. Numerous data on productivity enhancement studies from Africa and Asia demonstrate huge potential to enhance green WUE as well as increasing availability of green water (Wani et al. 2002, 2003a, 2008, 2009b, 2011c; Rockström et al. 2007, 2010; Barron and Keys 2011).

13.4.1 IMPORTANCE OF GREEN WATER MANAGEMENT IN RAINFED AGRICULTURE

Most of the 1338 million poor people in the world live in the developing countries of Asia and Africa, more so in drylands/rainfed areas (Rockström et al. 2007; Wani et al. 2009a, 2011b). Approximately 50% of total global land area is located under dry and arid regions (Karlberg et al. 2009). The importance of rainfed agriculture varies regionally, but it produces most food for poor communities in developing countries (Rockström et al. 2007; Wani et al. 2011a). In SSA more than 95% of the farmed land is rainfed, while the corresponding figure for Latin America is almost 90%, for South Asia about 60%, for EA 65%, and for the Near East and North Africa 75% (FAOSTAT 2010) (Table 13.2). A large fraction of the global expansion in the total cropland since 1900 is in rainfed regions (Figure 13.6). Native vegetation such as forests and woodlands were converted into croplands (mostly into rainfed agriculture) and grasslands, which produced more staple food and animal proteins but also, in the event of severe land degradation, depletion of soil nutrients and loss of biodiversity, which resulted in poor productive status as well as loss in system resilience and ecosystem services (Gordon et al. 2005). Most countries in the world depend primarily on rainfed agriculture for their grain food and a great number of poor families in many developing countries such as Africa and Asia still face poverty, hunger, food insecurity, and malnutrition, where rainfed agriculture is the main agricultural activity. These problems are exacerbated by adverse biophysical growing conditions and the poor socioeconomic infrastructure in many areas in the arid, semiarid tropics (SAT), and the subhumid regions (Wani et al. 2011a). In other words, where water limits crop production, poverty is strongly linked to variations in rainfall and to the farmers' ability to bridge intraseasonal dry spells (Karlberg et al. 2009).

TABLE 13.2
Global and Continentwise Rainfed Area and Percentage of Total Arable Land

Continent Regions	Total Arable Land (million hectares)	Rainfed Area (million hectares)	Percentage of Rainfed Area
World	**1551.0**	**1250.0**	**80.6**
Africa	*247.0*	*234.0*	*94.5*
Northern Africa	28.0	21.5	77.1
Sub-Saharan Africa	218.0	211.0	96.7
Americas	*391.0*	*342.0*	*87.5*
Northern America	253.5	218.0	86
Central America and Caribbean	15.0	13.5	87.7
Southern America	126.0	114.0	90.8
Asia	*574.0*	*362.0*	*63.1*
Middle East	64.0	41.0	63.4
Central Asia	40.0	25.5	63.5
Southern and Eastern Asia	502.0	328.0	65.4
Europe	*295.0*	*272.0*	*92.3*
Western and Central Europe	125.0	107.5	85.8
Eastern Europe	169.0	164.0	97.1
Oceania	*46.5*	*42.5*	*91.4*
Australia and New Zealand	*46.0*	*42.0*	*91.3*
Other Pacific Islands	*0.57*	*0.56*	*99.3*

Source: FAO. AQUASTAT database. 2010. http://www.fao.org/nr/aquastat; FAO. FAOSTAT database. 2010. http://www.faostat.fao.org/.

13.4.2 VAST POTENTIAL TO ENHANCE WATER PRODUCTIVITY IN THE TROPICS

A linear relationship is generally assumed between biomass growth and vapor flow (ET), which describes WP in the range between 1000 and 3000 m^3/t for grain production (Rockström 2003) (Figure 13.10). Increasingly, it is recognized that this linear relationship does not hold true for yields up to 3 t/ha, which exactly coincide with yield levels of small and marginal farmers in dryland/rainfed areas. The reason is that improvements in agricultural productivity, resulting in yield increase and denser foliage, will involve a vapor shift from nonproductive evaporation (E) in favor of productive transpiration (T) and a higher T/ET as transpiration increases (essentially linearly) with higher yield (Stewart et al. 1975; Rockström et al. 2007). Therefore, this is a huge scope for improving WP through green water management especially at lower yield level (Figure 13.10), and agricultural water interventions can help in reducing the water stress situation by enhancing green water availability. Evidence from water balance analyses on farmers' fields around the world shows that only a small fraction, less than 30% of rainfall, is used as productive green water flow (plant transpiration) supporting plant growth (Rockström 2003). In arid areas typically as little as 10% of the rainfall is consumed as productive green water flow (transpiration), while 90% of the flows constitute nonproductive evaporation flow, that is, no or very limited blue water generation (Oweis and Hachum 2001). In temperate arid regions, such as West Africa and North Africa, a large portion of the rainfall is generally consumed in the farmers' fields as productive green water flow (45%–55%), which results in higher yield levels (3–4 t/ha as compared with 1–2 t/ha) and 25%–35% of the rainfall flows as nonproductive green water flow while the remaining 15%–20% generates blue water flow. Agricultural water interventions in the watershed in Indian SAT reduced runoff amount by 30%–50%, depending on the rainfall distribution and converted more of it into green water (Figure 13.11; Garg et al. 2011a).

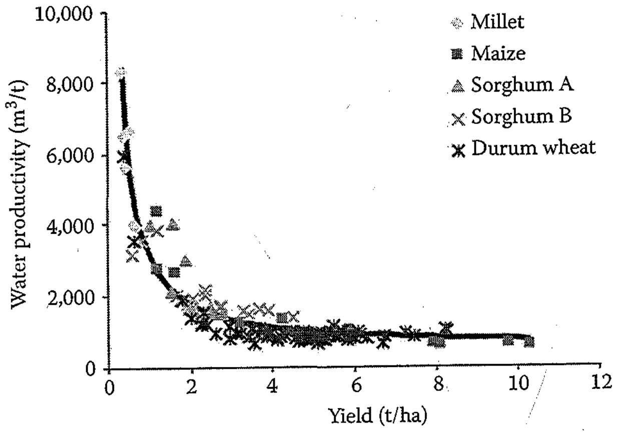

FIGURE 13.10 Dynamic relationship between green water productivity and yield for cereal crops in different climatic conditions and management. (Data from Rockström et al. (1998) (Millet); Stewart (1988) (Maize); Dancette (1983) (Sorghum A); Pandey et al. (2000) (Sorghum B); and Zhang and Oweis (1999) (Durum Wheat). Regression line after Rockström (2003). (From Karlberg, L., Rockström, J., Falkenmark, M., et al., In *Rainfed Agriculture: Unlocking the Potential*, pp. 1–310, The Comprehensive Assessment of Water Management in Agriculture Series, Volume 7, CABI, Wallingford, UK, 2009.)

There is a vast untapped potential in rainfed areas with appropriate soil and water interventions (Rockström and Falkenmark 2000; Wani et al. 2003a, 2009a, 2011a,b,c; Rockström et al. 2007, 2010; Figures 13.12 and 13.13).

Even in tropical regions, particularly in the subhumid and humid zones, agricultural yields in commercial rainfed agriculture exceed 5–6 t/ha (Rockström and Falkenmark 2000; Wani et al. 2003a,b; Figure 13.13). At the same time, the dry subhumid and semiarid regions have experienced the lowest yields and the weakest yield improvements per unit land. Here, yields oscillate between 0.5 and 2 t/ha, with an average of 1 t/ha in SSA and 1–1.5 t/ha in South Asia, Central Asia, West Asia, and North Africa for rainfed agriculture (Rockström and Falkenmark 2000; Wani et al. 2003a,b). Data of a long-term experiment at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT's) Heritage watershed site (Figure 13.13) has conclusively established that integrated IWRM interventions' average crop yield is fivefold higher compared with traditional practices (Wani et al. 2003a, 2011a,b). Similar results were also recorded at Kothapally watershed where implementing IWRM interventions enhanced crop yields almost two to three times as compared with that in 1998 prior to such interventions (Wani et al. 2003a; Sreedevi et al. 2004).

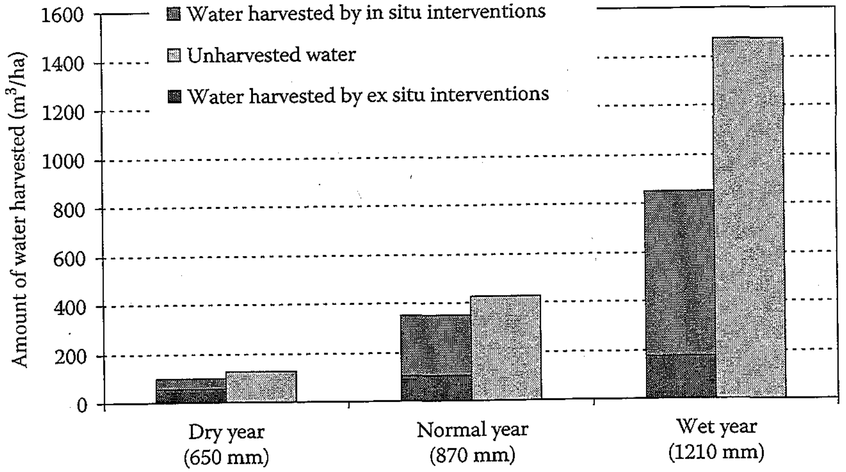

FIGURE 13.11 Fraction of runoff harvested in blue and green water from unharvested amount by implementing various agricultural water interventions compared to nonintervention stage.

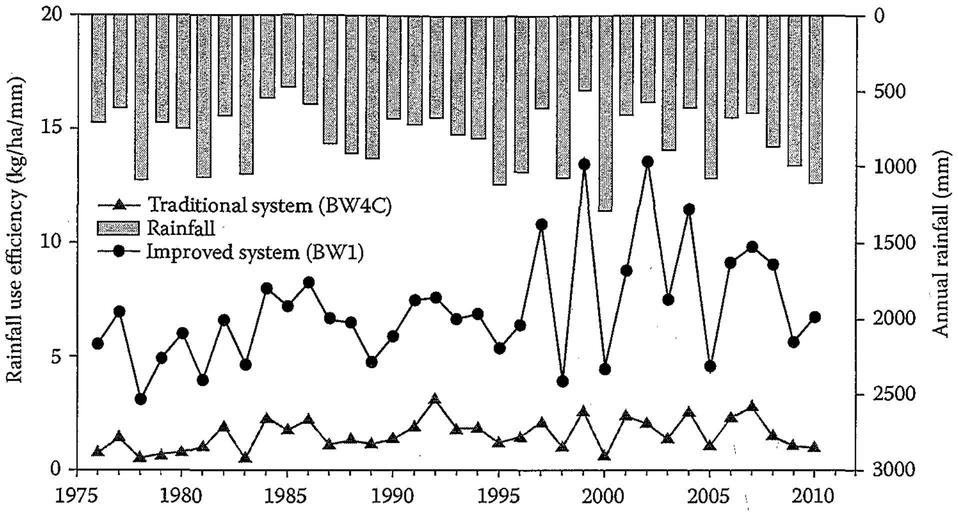

FIGURE 13.12 Increased rainwater-use efficiency in low rainfall years in a long-term experiment at Heritage watershed site, ICRISAT, Patancheru, India.

Yield gap analyses carried out for comprehensive assessment, for major rainfed crops in semiarid regions in Asia and Africa and rainfed wheat in West Africa and North Africa, revealed large yield gaps with farmers' yields being a factor of 2–4 times lower than achievable yields for major rainfed crops (Figures 13.14 and 13.15 and Table 13.3). Detailed yield gap analyses of major rainfed crops in different parts of the world have been discussed by Fisher et al. (2009) and Singh et al. (2009). In eastern and southern African countries, the yield gap is very large (Figure 13.15). Similarly, in many countries in

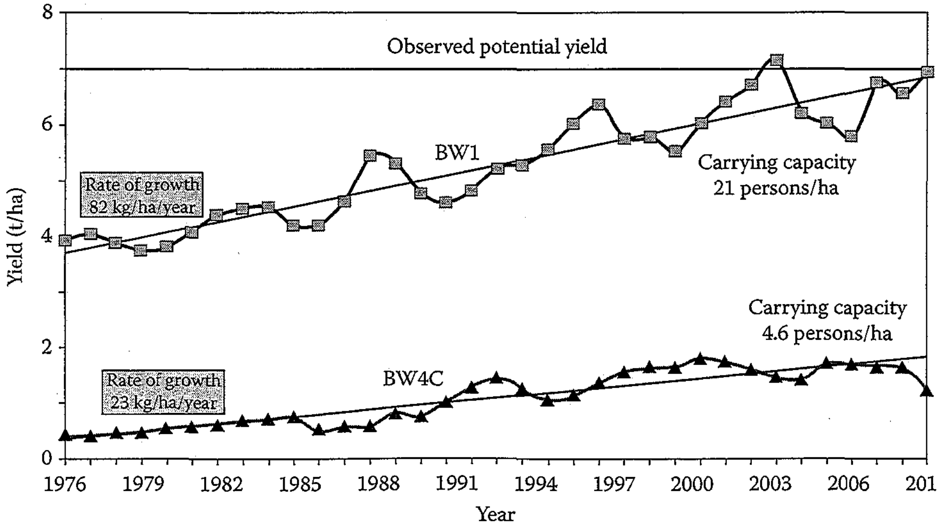

FIGURE 13.13 A comparison of harvested grain yield by implementing IWRM techniques in BW1 Vertisol watershed at ICRISAT with traditional farmers' practices at BW4C; results are shown since 1976 onward.

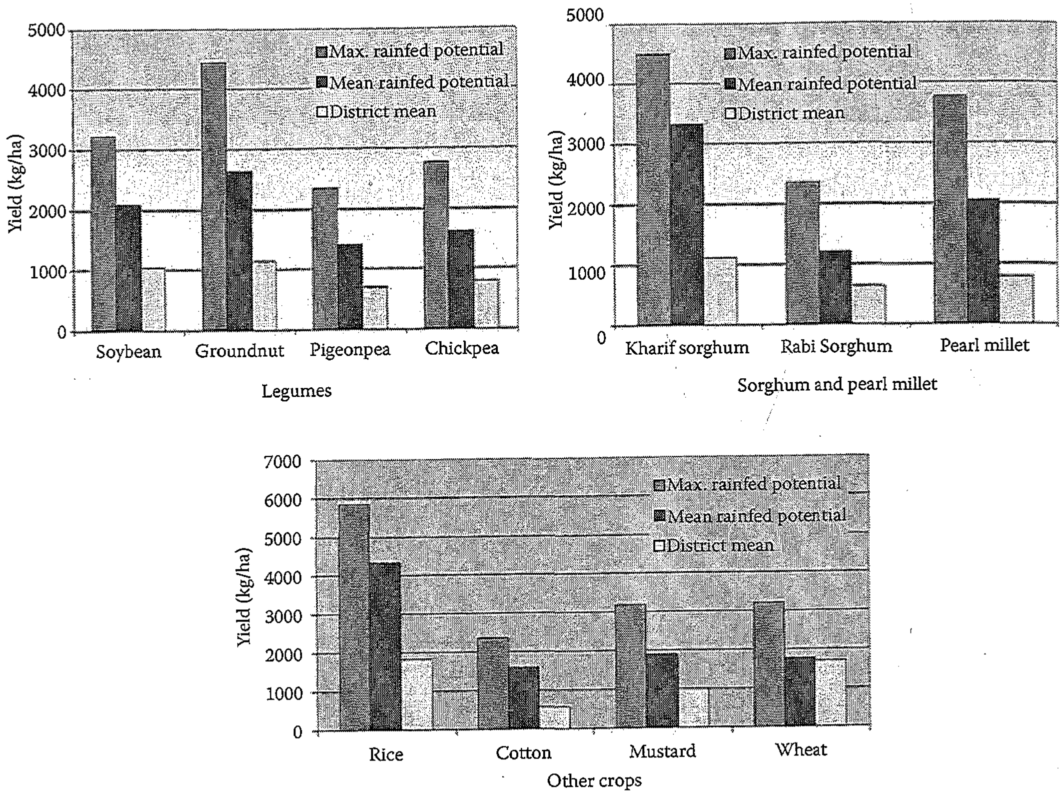

FIGURE 13.14 Rainfed potential yields and yield gaps of crops in India. (From Singh, P., Aggarwal, P.K., Bhatia, V.S., et al., *Yield Gap Analysis: Modeling of Achievable Yields at Farm Level in Rain-Fed Agriculture: Unlocking the Potential*, pp. 81–123, CAB International, Wallingford, UK, 2009.)

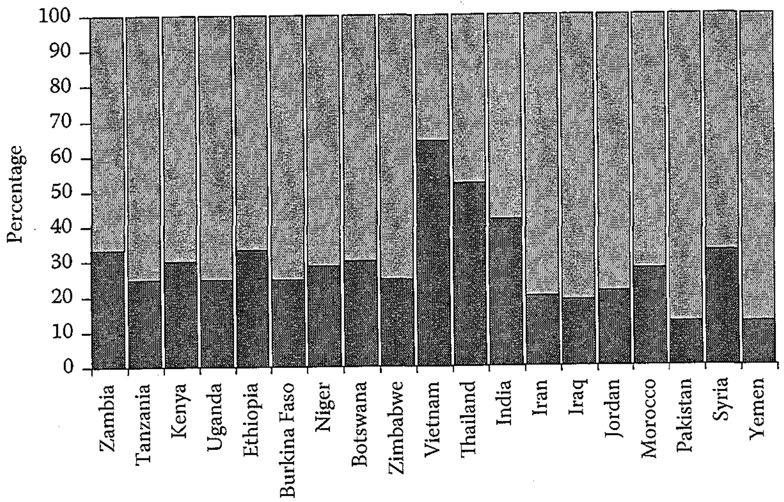

FIGURE 13.15 Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level, and columns actual observed yield levels). (From Rockström, J., Hatibu, N., Oweis, T., et al., In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, Earthscan, London and International Water Management Institute (IWMI), Colombo, Sri Lanka, 2007.)

TABLE 13.3
Yield Gap Analysis of Soybean Crop in Selected Benchmark Location in India

Seasonal Rainfall (mm)	Crop Analyzed	Number of Benchmark Location Analyzed	Observed Crop Yield (kg/ha) Mean	Observed Crop Yield (kg/ha) Maximum	Rainfed Yield (Simulated) Potential (kg/ha) Mean	Rainfed Yield (Simulated) Potential (kg/ha) Maximum	References
600–700	Soybean	2	730	910	1200	3190	Singh et al. (2001)
700–800		7	840	1000	1930	3070	
800–900		2	860	840	1750	3110	
900–1000		10	790	930	1950	3330	
1000–1100		5	820	860	2200	3350	
1100–1200		2	770	770	1960	3200	
300–400	Groundnut	2	1045	1390	1020	3495	Bhatia et al. (2009)
400–500		2	615	730	2050	4710	
500–600		3	1417	1790	2860	4897	
600–700		5	900	1120	2642	5030	
700–800		4	1150	1550	3425	4978	
800–900		2	820	860	3935	5655	
300–400	Pigeonpea	1	310	310	920	1810	Bhatia et al. (2006)
400–500		3	350	470	1083	2130	
500–600		2	310	430	1490	2305	
600–700		6	647	910	1260	2198	
700–800		7	478	1040	1681	1963	
800–900		8	513	1140	1790	2405	
900–1000		3	623	930	1453	2140	
>1000		5	306	640	1856	2110	
Postmonsoon crop	Chickpea	26	715 (330–1050)	1050	1130 (490–2030)	2470 (1090–4300)	Bhatia et al. (2006)

Source: Singh, P., Vijaya, D., Srinivas, K., et al., Potential productivity, yield gap, and water balance of soybean-chickpea sequential system at selected benchmark sites in India. Global Theme 3: Water, Soil, and Agrobiodiversity Management for Ecosystem Heath. Report no.1. Patancheru 502 324, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India, 2001.

West Asia, farmers' yields are less than 30% of achievable yields, while in some Asian countries the figure is closer to 50%. Historic trends present a growing yield gap between farmers' practices and farming systems that benefit from management advances (Wani et al. 2003b, 2009a, 2011a).

13.5 NEW PARADIGM TO OPERATIONALIZE IWRM IN RAINFED AREAS

Business as usual to manage rainfed agriculture as subsistence agriculture with low resource use efficiency cannot sustain economic growth and is needed for ensuring food security to the growing population with increasing incomes (Wani et al. 2002, 2009a, 2011a; Molden et al. 2007; Rockström et al. 2007). There is an urgent need to develop a new paradigm for operationalizing the IWRM framework to harness the untapped potential of rainfed agriculture. The conventional sectoral approach to water management produced low WUE, resulting in increased demand for water to produce food while also causing degradation of natural resources. We need to have a holistic approach based on the convergence of all the necessary aspects of natural resource conservation, their efficient use, production functions, and income enhancement avenues through the value chain and enabling policies and much-needed investments in rainfed areas.

The policy on water resource management for agriculture conventionally remains focused on irrigation, and the framework for IWRM at catchment and basin scales is primarily concentrated on allocation and management of blue water (irrigation water) in rivers, groundwater, and lakes. The evidence from the comprehensive assessment indicated that water for agriculture is more than for irrigation, and there is an urgent need for a widening of the policy scope to include explicit strategies for water (green and blue) management in rainfed agriculture including grazing and forest systems. Effective integration is necessary to focus on the investment options on water management across the continuum (range) from rainfed to irrigated agriculture. This is the time to abandon the obsolete sectoral divide between irrigated and rainfed agriculture, which would place water resource management and planning more centrally in the policy domain of agriculture at large, and not as today, as a part of water resource policy (Molden et al. 2007).

Furthermore, the current focus on water resource planning at the river basin scale is not appropriate for water management in rainfed agriculture, which overwhelmingly occurs on farms of <5 ha at the scale of small catchments, below the river basin scale. Therefore, focus should be on managing water at the catchment scale (or small tributary scale of a river basin) and initiating the much-needed investments in water resource management also in rainfed agriculture (Wani et al. 2002, 2009a, 2011a; Rockström et al. 2007, 2010; Kijne et al. 2009; Wilson 2011).

The world's available land and water resources can satisfy future demands by taking the following steps (Molden et al. 2007):

- Upgrading rainfed agriculture by investing more in rainfed agriculture to enhance agricultural productivity (rainfed scenario)
- Discarding the artificial divide between rainfed and irrigated agriculture and adopting the IWRM approach for enhancing resource efficiency and agricultural productivity
- Investing in irrigation for expanding irrigation where scope exists and improving efficiency of the existing irrigation systems (irrigation scenario)
- Recycling wastewater (gray water) for fodder and food production after suitable treatment
- Conducting agricultural trade within and between countries (trade scenario)
- Reducing gross food demand by influencing diets and reducing postharvest losses, including industrial and household waste

To upgrade rainfed agriculture in the developing countries, community participatory and integrated watershed management approach is recommended and success has been proved as evidenced from a number of islands of Asia and Africa (Wani et al. 2002, 2003a, 2009a, 2011a; Rockström et al. 2007; Wilson 2011). In the rainfed areas of the tropics, water scarcity and growing land degradation cannot be tackled through farm-level interventions alone and community-based management of natural resources for enhancing productivity and improving rural livelihoods is urgently needed (Wani et al. 2002, 2009a; Rockström et al. 2007, 2010). A major research and development challenge to upgrade rainfed agriculture is to bring in convergence among different stakeholders and scientific disciplines by coming out of disciplinary silos and to translate available blueprints into operational plans and implement them (Wani et al. 2003a, 2006, 2009a, 2011a; Rockström et al. 2007, 2010). We know what to do but the challenge is how to do it (Wani et al. 2008, 2011a).

The community-based management of natural resources calls for new approaches (technical, institutional, and social) that are knowledge-intensive and need strong capacity development (more than training of human resources) for all the stakeholders including policy makers, researchers, development agents, and farmers. The small and marginal farmers are deprived of the new knowledge and materials produced by the researchers. There are several disconnects between the farmers and the researchers as the extension systems in most developing countries are not functioning to the desired level. There is an urgent need to bring in the changes in the ways we are addressing the issues of rainfed agriculture to achieve food security and alleviate poverty to meet the Millennium Development Goals (MDGs) (Rockström et al. 2007; Wani et al. 2008, 2009, 2011a,b; Wilson 2011).

13.5.1 NEED FOR HOLISTIC INTEGRATED APPROACH TO HARNESS THE FULL POTENTIAL

Farmers who are solely dependent on agriculture, especially in dry lands, face a high level of uncertainty and risk of failure due to various extreme climatic events, pest and disease attack, and market shocks. Therefore, integration of agriculture (on-farm) and nonagriculture (off-farm) activities is required for generating consistent source of income and support for livelihood. For example, agriculture, livestock production, and dairy farming system together can be more resilient and sustainable compared with adopting agriculture practice alone. The product or by-product of one system could be utilized for the other and vice versa.

This approach suggests the integration of technologies within the natural boundaries for optimum development of land, water, and plant resources to meet the basic needs of people and animals in a sustainable manner. The holistic approach focuses on (i) conservation, upgradation, and utilization of natural endowments such as land, water, plant, animal, and human resources in a harmonious and integrated manner with low-cost, simple, effective, and replicable technology; and (ii) reduction of inequalities between irrigated and rainfed areas and poverty alleviation. Thus, this approach aims to improve the standard of living of common people by increasing their earning capacity by making available all facilities required for optimum production and disposal of marketable surplus (Wani et al. 2006b). This approach suggests adopting land and water conservation practices, water harvesting in ponds, and recharging of groundwater for increasing the potential of water resources, and emphasizes on crop diversification, use of improved variety of seeds, integrated nutrient management (INM), and integrated pest management (IPM) practices.

13.5.2 INTEGRATED WATERSHED MANAGEMENT FOR SUSTAINABLE INTENSIFICATION OF RAINFED AGRICULTURE

It is well documented (Wani et al. 2007, 2008; Joshi et al. 2008) that the watershed management program is one of the most suitable options for increasing WUE and also as an adaptive strategy to cope with climate change impact in rainfed areas (Wani et al. 2002, 2009a, 2011a; Mujumdar 2008; Batisani and Yarnal 2010; Feng et al. 2010; Hanjra and Qureshi 2010; Barron and Keys 2011; Wilson 2011). The watershed development program recorded increased soil and water conservation with concomitant retention of more rainwater through several in situ (green water) and ex situ interventions of blue water at the farm (micro) and watershed/catchment (meso) scale and augmented its use within the boundary of the landscape (Samra and Eswaran 2000; Wani et al. 2008, 2011a,b; Barron and Keys 2011; Wilson 2011). Wani et al. (2009a) described the watershed scale as the "entry point" for effective management of smallholder agroecosystems for improving livelihoods. Wilson (2011) described in detail the integrated watershed management for improving livelihoods and integrated rural development in developing countries, particularly in Asia and possibly in Africa. Further, Barron and Keys (2011) interpreted successes in watershed case studies in terms of overall agroecosystem stability, described watershed management through resilience, and suggested that "entry point" refer to a specific point of entry for managers or farmers to actively intervene in the dynamic smallholder rainfed agroecosystems.

Implementing watershed activities at smaller landscape levels probably may not realize actual benefits, as was clearly visible at the mesoscale level, as Joshi et al. (2005) observed that watersheds >1000 ha were more effective in economic, equity, and sustainability parameters. It is quite likely that farm pond/check dams built at one location may benefit groundwater recharge beyond the boundary of the implementation. Similarly generated groundwater recharge/water table may increase base flow at a further downstream location (Sreedevi et al. 2004; Wani et al. 2011a). The national program of watershed management in India has realized the scale issue as recommended (Wani et al. 2008) and has adopted 1000–5000 ha of watershed area for implementing the program with new common watershed guidelines (GoI 2008).

13.5.3 LEARNINGS FROM META-ANALYSES OF WATERSHED CASE STUDIES FROM INDIA

A descriptive summary of multiple benefits derived from 636 watersheds revealed that watershed programs are silently bringing about a revolution in rainfed areas with a mean benefit–cost (B/C) ratio of 2.0 with the benefits ranging from 0.82 to 7.30 (Table 13.4) and >99% of projects were economically remunerative. About 18% watersheds generated a B/C ratio above 3, which is fairly modest (Figure 13.16a). However, it also indicated a large scope to enhance the impact of 68% of watersheds that performed below an average B/C of 2.0. Merely 0.6% of the watersheds failed to commensurate with the cost of the project (Joshi et al. 2008).

The mean internal rate of return of 27.43% was significantly high and comparable with any successful government program (Table 13.4). The internal rates of return in 41% of watersheds were in the range of 20%–30%, whereas about 27% of watersheds yielded IRR of 30%–50% (Figure 13.16b). The watersheds with IRR below 10% were only 1.9%. Watershed programs generated significant and substantial employment opportunities in the watershed areas (Table 13.4), which means raising their purchasing power, resulting in alleviating rural poverty and income disparities. This has an important implication in the sense that the watershed investment may be considered as a poverty alleviation program in the fragile ecosystem areas (Joshi et al. 2008).

The estimates show that watershed programs were quite effective in addressing the problems of land degradation due to soil erosion and loss of water due to excessive runoff. Soil loss of about 1.12 t/ha/year was prevented due to interventions in the watershed framework. Conserving soil means raising farm productivity, increasing WUE, and preserving the good soils for the next generation. It was noted that on average, about 38 ha-m (10^4 cubic meters) additional water storage capacity was created in a watershed of 500 ha as a result of the watershed program. Augmenting water storage capacity contributed to (i) reducing rate of runoff by 46% and (ii) increasing groundwater recharge by 3.6 m on an average in the watershed areas. These had a direct impact on expanding the irrigated area, increasing cropping intensity, and diversifying systems with high-value crops. On an average, the irrigated area increased by about 52%, while the cropping intensity increased by 35.5%. In some cases the irrigated area increased up to 204% while the cropping intensity increased by 283%. Such an impressive increase in the cropping intensity was not realized in many surface-irrigated areas in the country. These benefits confirm that the watershed programs perform as a viable strategy to overcome several externalities arising due to soil and water degradation (Joshi et al. 2008).

The above evidence suggests that watershed programs, which have been specifically launched in rainfed areas with the sole objective of improving the livelihood of poor rural households in a sustainable manner, have paid rich dividends and were successful in raising income levels, generating employment opportunities, and augmenting natural resources in the rainfed areas. These benefits have far-reaching implications for rural masses in the rainfed environment, and watershed management is recommended as a growth engine for the rural development of rainfed areas (Wani et al. 2008).

The results of meta-analysis regression further showed that the benefits vary depending upon the location, size, type, rainfall pattern, implementing agency, and people's participation. It is also important to state that the focus of the watershed program, status of the target population, and people's participation are some of the critical factors that play a deterministic role in the performance and efficiency of watersheds (Joshi et al. 2008). The drivers of success of watershed programs through increased efficiency (Wani et al. 2008) are discussed below:

- Macro watersheds (>1200 ha) achieved better impact than micros of 500 ha. Development activities need to be undertaken in clusters of at least four to six micro watersheds (2000–3000 ha).
- Available technologies are effective between 700 mm and 1100 mm of rainfall zone and the principle of "one size fits all" does not work. There is an urgent need to evaluate technologies for <500 and >1100 mm annual rainfall zones.

TABLE 13.4
Summary of Benefits from the Sample Watersheds Using Meta-Analysis

	Particulars	Unit	Number of Studies	Mean	Mode	Median	Minimum	Maximum	t-Value
Efficiency	B/C	Ratio	311	2.01	1.70	1.70	0.82	7.30	35.09
	IRR	percent	162	27.43	25.90	25.00	2.03	102.70	21.75
Equity	Employment	person days/ha/year	99	154.53	286.67	56.50	0.05	900.00	8.13
Sustainability	Increase in irrigated area	percent	93	51.55	34.00	63.43	1.28	204.00	10.94
	Increase in Cropping intensity	percent	339	35.51	5.00	21.00	3.00	283.00	14.96
	Runoff reduced	percent	83	45.72	43.30	42.53	0.38	96.00	9.36
	Soil loss saved	t/ha/year	72	1.12	0.91	0.99	0.11	2.05	47.21

Source: Joshi, P.K., Jha, A.K., Wani, S.P., et al., Impact of watershed program and conditions for success: A meta-analysis approach. In *Global Theme on Agroecosystems*, Report no. 46. Patancheru 502 324, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India, 2008.

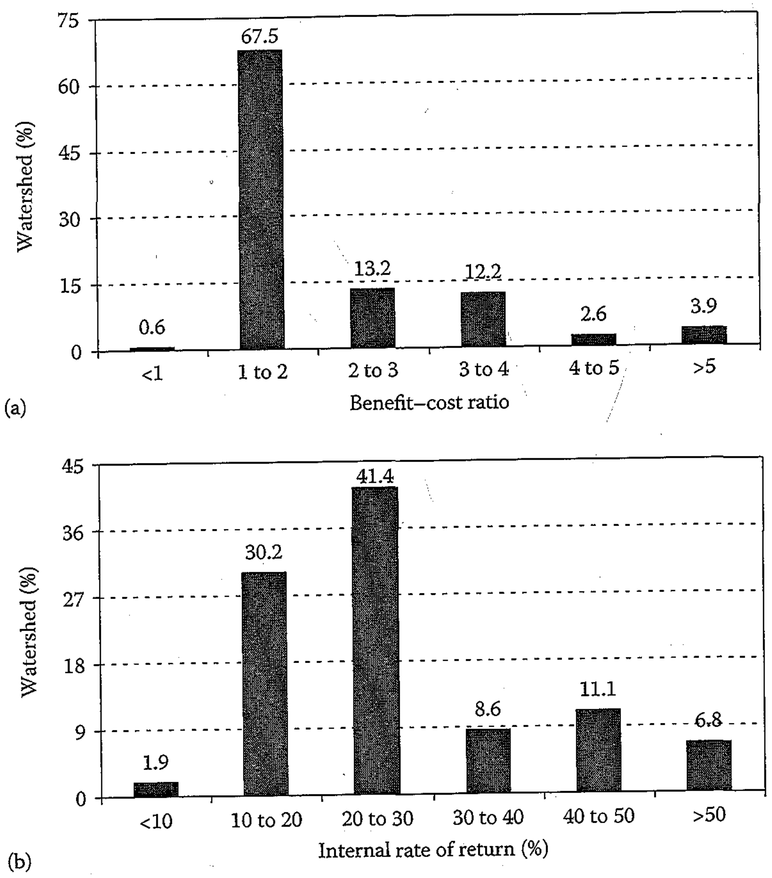

FIGURE 13.16 (a) Distribution (%) of watersheds according to benefit–cost ratio (BCR). (b) Distribution (%) of watersheds according to internal rate of return (IRR). (From Joshi, P.K., Jha, A.K., Wani, S.P., et al., Impact of watershed program and conditions for success: A metaanalysis approach. In *Global Theme on Agroecosystems,* Report no. 46. Patancheru 502 324, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India, 2008.)

- Use of new scientific tools such as crop simulation and water balance models, GIS, remote sensing and information and communication technology (ICT), participatory research and development (PR&D), and collective action for planning, implementation, monitoring and evaluation (M&E) are needed to manage natural resources more efficiently and sustainably in the watersheds.
- The drivers of success are tangible economic benefits to a large number of people; empowerment through knowledge sharing; equal partnership, trust, and shared vision; good local leadership; transparency and social vigilance in financial dealings; equity through low-cost structures; predisposition to work collectively; activities targeted at the poor and women; increased drinking water availability; and income-generating activities for women.
- The current allocations are insufficient to "treat" a complete watershed or to adopt the livelihood approach. Higher investments are a must to make watersheds engines of growth. The Government of India (GoI) has increased investments in new integrated watershed management programs (IWMP) from (Indian rupees) 6,000 (USD 133) to 12,000 (USD 266) per ha in plains and 15,000 (USD 333) in hilly areas (GoI 2008) and has adopted a livelihood approach to ensure tangible economic benefits to people in a watershed.

- Reduction of costs through convergence of action to avoid duplication, costs of environment deterioration, and enhancing efficiency of interventions.
- Interventions to benefit women and vulnerable groups have developed social capital and increased sustainability.
- Impact on production, poverty, the environment, and community involvement was achieved through capacity building. In order to effectively implement programs, the implementing agencies need to expand and broaden their capacities, skills and reach; and communities need to strengthen their institutions and skills. This will require a longer implementation period of 7–8 years with more time spent in preparation and in postintervention support. There is a need for additional funds and more flexibility in using budgets, as well as the engagement of specialist service providers. New common guidelines (GoI 2008) have addressed these recommendations and the project duration is increased up to 7 years with 5% of the total budget earmarked for capacity building using the services of quality service providers.
- New technologies and technical backstopping improved the performance of watershed programs. Forming consortia and employing agencies to provide specialist technical backstopping through a National Support Group (NSG) are needed.
- Improved and concurrent M&E and constant feedback improved performance. Detailed monitoring of one or two representative watersheds in each district for a broad range of technical and socioeconomic parameters measured provided a scientific benchmark and a better economic valuation of impact through scaling-up using bioeconometric and social models.

13.5.4 Business Model

Watersheds should be seen and developed as a business model. This calls for a shift in approach from subsidized activities to knowledge-based entry points and from subsistence to marketable surplus, ensuring tangible economic benefits for the population of the watershed at large. This is being done with productivity enhancement, diversification to high-value enterprises, income-generating activities, market links, public–private partnerships, microentrepreneurship, and broad-based community involvement. Strengths of rainfed areas using available water resources efficiently through involvement of private entrepreneurs and value addition can be harnessed by linking small and marginal farmers to markets through a public–private partnership business model for watershed management (Wani et al. 2008).

13.5.5 Rainwater Conservation and Harvesting: An Entry Point for Sustainable Intensification

In situ interventions and land management such as field and contour bunding, conservation agriculture (CA), and minimum tillage practices can enhance infiltration capability and convert more rainfall into green water (Wani et al. 2003a, 2008, 2009; Rockström et al. 2007; Garg et al. 2011a). In addition, soil organic matter augmentation, improved crop agronomy options, balanced plant nutrition, improved crops and crop varieties, crop protection, crop intensification through double cropping, contingency cropping, and reduction of rainy season fallows and rice fallows play an important role in enhancing green WUE by plants (Wani et al. 2009a, 2011b; Singh et al. 2011).

Agricultural water interventions, especially ex situ interventions, are helpful in enhancing blue water resources in watersheds as well as downstream areas (Wani et al. 2003a; Pathak et al. 2009, 2011; Glendenning and Vervoort 2011). Rainwater harvesting (RWH) has great potential of contributing to poverty reduction efforts by improving agricultural productivity and profitability in rainfed areas in Africa and Asia (Wani et al. 2002, 2009a, 2011a,b; Rockström et al. 2007; Pathak et al. 2009, 2011; Oweis and Hachum 2009; Sharma et al. 2010; Mati et al. 2011). Low-cost water-harvesting structures such as check dams and farm ponds could be constructed using available local expertise and materials (Wani et al. 2003b, 2011a; Pathak et al. 2007). This water could directly be used for supplemental irrigation or to enhance groundwater recharge, and with increased water availability, farmers can shift from low-value crops to cultivate high-value vegetables, fruit trees, and other cash crops (Wani et al. 2009a, 2011a). Moreover, it reduces flash flood, enhances nonerosive base flow, and also helps in reducing soil and nutrient loss.

Unlike the green revolution in Asia, the African agricultural sector is predominantly rainfed, even in ecological zones, which by necessity should be fully or partially irrigated. Currently, 4% of water resources have only been developed for agriculture, water supply, and hydropower use in Africa compared with 70%–90% in Asia and developed countries (Mati 2010). Moreover, RWH techniques build reliance against extreme events such as long dry spells upstream and flood-type situations downstream (Reij et al. 1996; Mati 2005; Mati et al. 2011; Wani et al. 2006b, 2011a).

13.5.6 STRATEGIES FOR ENHANCING WATER PRODUCTIVITY IN RAINFED AREAS

There are several climatic and land management factors responsible for crop growth, crop yield, and crop WP in dryland agriculture. For example, soil water availability, nutrient/fertility status, selection of right crop/variety, supplemental irrigation, and pest and disease infestation are among a few. Selection of crop/variety should be based on the length of growth period such that it has high probability to attain production successfully. Various agricultural water interventions increase soil moisture availability and are particularly helpful during long dry spells.

13.5.7 FIELD-SCALE INTERVENTIONS TO SHIFT WATER VAPOR LOSSES THROUGH EVAPOTRANSPIRATION

13.5.7.1 Crop Intensification through Land Surface Management

Intercropping or mixed cropping systems are more resilient compared with monocropping system in rainfed areas due to efficient and better utilization of resources such as green water, soil nutrients, and light. These systems are also stable under adverse weather and pest/disease situations. Land smoothening and forming of field drains are basic components of land and water management for conservation and safe removal of excess water in a guided manner. Broad bed and furrow (BBF) system is an improved in situ soil and moisture conservation and drainage technology for clayey soils with low infiltration rate as soil profile gets saturated and waterlogged with the progression of the rainy season (El-Swaify et al. 1985).

Data from long-term research trials at ICRISAT show that management of Vertisols with improved management options and interventions improved soil physical, chemical, and biological properties of micro watersheds. Field-scale intervention of improved management comprises sowing of crops on graded BBF of 45 cm as practice for in situ soil and water conservation and safe disposal of excess runoff during heavy downpour. The rainy season crops (sole and intercrops) along with pigeonpea/maize/sorghum/soybean/green gram were sown in the dry bed prior to the onset of monsoon rains, and two crops were grown annually in rotation. Fertilizer management involved the application of 80 kg N and 40 kg P_2O_5 per hectare. Under traditional practice, the seedbed was kept flat, and one crop, either sorghum or chickpea, was grown during the postrainy season utilizing the stored soil moisture in the profile. No mineral fertilizers were added, and farmyard manure (FYM) was added at 10 t/ha every 2 years. Results show that improved management significantly increased soil porosity, infiltration rate, and carbon content compared with traditionally managed fields (Table 13.5). Such changes in the biophysical properties also led to changes in the hydrological cycle as runoff was reduced in BBF fields and stored more rainfall into green water form. A significant amount of total rainfall is used in productive transpiration; therefore, crop yields in BBF fields were found consistently higher than 4.5 t/ha, irrespective of several deficit and surplus water years (Wani et al. 2003a, 2011b; Pathak et al. 2005). On the other hand, average crop yield in traditionally managed fields was found to be 0.9 t/ha. Average crop WP of BBF fields was found to be 0.65 kg/m³ compared with 0.15 kg/m³ in traditionally managed fields (Table 13.5).

TABLE 13.5
Effects of Long-term Landform Treatment on Physical, Chemical, and Biological Soil Properties of Micro Watershed and Its Impact on Hydrology, Crop Yield, and Water Productivity at the ICRISAT, Heritage Watershed Site in Patancheru, India (1976 and 1998)

Parameter	Improved System	Traditional System
Land management practices	Broad bed and furrow	Flat land
Cropping system and its rotation	*First year:* maize followed by chickpea *Second year:* sorghum intercropped with pigeonpea	Sorghum or chickpea
Fertilizer application per hectare	80 kg N and 40 kg P_2O_5	FYM every 2 years (10 t/ha)
Biophysical properties of soil		
Bulk density of surface soil (g/cm³)	1.2	1.5
Air-filled porosity (%)	41	33
Penetration resistance (M Pa)	1.1	9.8
Sorptivity (mm/30 min)	121	100
Cumulative infiltration in 1 h (mm)	347	205
Chemical properties of soil		
Organic C in 0–60 cm soil (t/ha)	27.4	21.4
Total N (kg/ha)	2684	2276
Organic carbon content in 0–120 cm soil (t/ha)	46.8	39.5
Biological properties in 0–60 cm soil		
Soil respiration (kg C/ha per 10 days)	723	260
Microbial biomass C (kg C/ha)	2676	2137
Microbial biomass N (kg N/ha)	86.4	39.2
Hydrology and soil loss		
Average annual rainfall in 1974–1982 (mm)	823	823
Surface runoff (mm)	112 (13.6%)	207 (25.1 %)
Soil loss (t/ha)	1.5	6.5
Crop yield and water productivity		
Grain yield between 1976 and 2006 (t/ha)	4.5	0.9
Increasing average yield rate (kg/ha/year)	82	23
Carrying capacity (person/year)	21	4.6
Crop water productivity (kg/m³)	0.65	0.15

On-farm trials on land management of Vertisols of central India revealed that the BBF system resulted in a 35% yield increase in soybean during the rainy season and yield advantage of 21% in chickpea during postrainy season compared with the farmers' practice. A similar yield advantage was recorded in maize and wheat rotation under the BBF system (Table 13.6a). Yield advantage of 15%–20% was recorded in maize, soybean, and groundnut with conservation furrows on Alfisols over farmers' practices at Haveri, Dharwad, and Tumkur watersheds in Karnataka (Table 13.6a).

TABLE 13.6a
Impact of IWRM-Based Intervention on Crop Yields at Different Benchmark Locations and Farm Fields in India and Elsewhere

Study Location/Benchmark Site	Interventions Made	Parameter Identified/ Estimated	Before/without Interventions	After/with Interventions	Impact Achieved	Data Source
Sujala Watershed, Karnataka, India	Contour cultivation along with conservation furrows	Crop yields (t/ha)	1.7 (1.2–3.4)	2.0 (1.4–3.9)	20% increased	Sujala-ICRISAT watershed project, Terminal Report (2008)
Vidisha, Sagar, Guna, Sehore and Raisen (MP, India) (170 farmers)	Land form treatment (bbf) + micro nutrient application	Soybean yield (t/ha)	1.9 (1.5–2.5)	2.3 (1.7–2.9)	20% increased	water-use efficiency project, Completion Report (2009)
Ginchi, Akaki in Ethiopia	Land form treatment (bbf)	Wheat yield (t/ha)	0.8–0.9	1.2–1.5	60% increased	Srivastava et al. (1993)
Sahel (1998–2000)	Supplemental irrigation and fertilizer application	Sorghum yield (t/ha)	0.45 (0.25–0.65)	1.4 (0.9–1.8)	210% increased	Fox and Rockstrom (2003)
Jhansi, Bengaluru and Indore, India	One supplemental irrigation of 40 mm in monsoon	maize, millet, soybean yield (t/ha)	2.2 (average)	2.8 (average)	30% increased	Vijayalakshmi (1987)
Andhra Pradesh, India (2002–2004)	Micro-nutrient s, b, zn + n p application	Maize yield (t/ha)	2.6	4.3	65% increased	Rego et al. (2005)
	Micro-nutrient s, b, zn + n p application	Groundnut yield (t/ha)	0.75	1.1	55% increased	
Vietnam (2000)	Mulching in groundnut	Groundnut yield (t/ha)	5.3	6.3	19% increased	Ramakrishna et al. (2006)
Vietnam (Spring 2001)	Nutrient management	Groundnut yield (t/ha)	5.5	6.6	20% increased	Ramakrishna et al. (2006)
		Biomass yield (t/ha)	9.5	11.3	19% increased	
Haveri, Karnataka, India	Contour cultivation (year 2006–2008)	Maize yield (t/ha)	3.35	3.89	16% increased	ICRISAT (2008) and Pathak et al. (2011)
Dharwad, India	Contour cultivation (year 2006–2008)	Soybean yield (t/ha)	1.47	1.8	23% increased	ICRISAT (2008) and Pathak et al. (2011)
Kolar, India	Contour cultivation (year 2006–2008)	Groundnut yield (t/ha)	1.23	1.43	16% increased	ICRISAT (2008) and Pathak et al. (2011)
Tumkur, India	Contour cultivation (year 2006–2008)	Finger millet yield (t/ha)	1.28	1.59	24% increased	ICRISAT (2008) and Pathak et al. (2011)
Guna	BBF + improved crop varieties + application of balanced fertilizer (total 140 farmers fields (covering 17 village in Madhya Pradesh, India))	Soybean yield (t/ha)	1.46	1.70	Increased (%) 16%	ICRISAT (2008)
Raisen			1.56	2.28	45%	
Videsha			1.72	2.23	30%	
Indore			2.51	2.90	15%	
Sehore			2.09	2.50	19%	
(during year 2007–2009)						
Ginchi, Ethiopia	Raised BBF	Wheat yield (t/ha)	0.83 (±0.08)	1.2 (±0.05)	46% increased	Srivastava et al. (1993)
Akaki, Ethiopia	Raised BBF	Wheat yield (t/ha)	0.96 (±0.06)	1.5 (±0.07)	54% increased	
Bellary, Karnataka, India 1988–1996	Vegetative barrier on resource conservation (land slope 1.5%)	Sorghum yield (t/ha)	0.47	0.78	35% increased	Rao et al. (2003)
Sahel 1998–2000	Supplemental irrigation	Sorghum yield (t/ha)	0.45 (±0.23)	0.71 (±0.32)	60% increased	Fox and Rockstrom (2003)
	Fertilizer application		0.45 (±0.23)	0.98 (±0.40)	120% increased	
	Supplemental irrigation + fertilizer application		0.45 (±0.23)	1.40 (±0.36)	210% increased	
Short duration rainy season	Supplemental irrigation (cm)	Yield (t/ha)			Increased (%)	Vijayalakshmi et al. (1987)
Hyderabad, India	1.6	Sorghum	0.38	2.51	560	
Jhansi, India	1.0	Maize	2.31	2.66	15	
Jhansi, India	2.0	Maize	3.16	4.43	40	
Bengaluru, India	5.0	Finger millet	1.56	2.23	43	
Indore, India	8.0	Soybean	1.80	2.05	14	
Long duration rainy season	Supplemental irrigation (cm)	Yield (t/ha)			Increased (%)	Vijayalakshmi et al. (1987)
Hyderabad, India	5.0	Castor	1.01	1.32	31	
Jhansi, India	3.0	Pigeonpea	0.05	0.17	240	
Jhansi, India	5.0	Pigeonpea	0.05	0.33	560	
Dantiwada, India	4.0	Tobacco	0.82	1.30	58	
Postrainy season	Supplemental irrigation (cm)	Yield (t/ha)			Increased (%)	Vijayalakshmi et al. (1987)
Dehradun, India	2.0	Wheat	1.17	1.58	35	
Dehradun, India	4.0	Wheat	1.17	2.06	78	
Dehradun, India	6.0	Wheat	1.17	2.60	123	
Ranchi, India	1.0	Rape seed	0.25	0.35	40	
Ranchi, India	3.0	Rape seed	0.25	0.46	84	
Ranchi, India	5.0	Rape seed	0.25	0.54	116	

(continued)

TABLE 13.6a (Continued)
Impact of IWRM-Based Intervention on Crop Yields at Different Benchmark Locations and Farm Fields in India and Elsewhere

Study Location/Benchmark Site	Interventions Made	Parameter Identified/ Estimated	Before/without Interventions	After/with Interventions	Impact Achieved	Data Source
ICRISAT, Patancheru, India	Supplemental irrigation (cm)	Chickpea yield (t/ha)			Increased (%)	Pathak et al. (2009)
	6.3		0.69	0.92	32	
	4.6		0.69	0.91	32	
ICRISAT, Patancheru, India Vertisol watershed	Supplemental irrigation	Yield (t/ha)			Increased (%)	Pathak et al. (2009)
		Maize chickpea	1.04	1.54	47	
		Mung-chilli	1.00	1.33	32	
		Maize-safflower	1.07	1.24	15	
Semiarid tropics, Andhra Pradesh, India (results based on total 286 farmers field during year 2002–2004)	Balanced nutrient management	Yield (t/ha)			Increased (%)	Rego et al. (2007)
		Maize	2.4–2.7	4.2–4.8	72	
		Castor	0.5–0.9	0.8–1.3	52	
		Mung bean	0.7–0.9	1.1–1.5	58	
		Groundnut	0.8–1.3	1.4–1.8	47	
		Pigeonpea	0.5–1.0	0.8–1.5	72	
Semiarid tropics, Karnataka, India (results based on total 992 farmers field during year 2005–2009)	Balanced nutrient management	Yield (t/ha)			Increased (%)	ICRISAT 2008
		Maize	4.0–5.6	5.4–8.7	44	
		Finger millet	1.6–2.1	2.1–3.2	49	
		Groundnut	0.9–1.8	1.4–2.1	35	
		Soybean	1.3–2.1	1.6–3.4	60	
Madhya Pradesh, India (results based on total 286 farmers field during year 2008–2009)	Balanced nutrient management	Yield (t/ha)			Increased (%)	ICRISAT 2008
		Soybean	1.49	1.84	23	
		Chickpea	1.25	1.44	15	
Rajasthan, India (results based on total 33 farmers field during year 2008)	Balanced nutrient management	Yield (t/ha)			Increased (%)	ICRISAT2008
		Maize	2.7	2.9	20	
		Pearl millet	2.3	2.5	20	

Yield advantage and rainfall use efficiency (RUE) were also reflected in cropping systems 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/mm under BBF systems across various cropping systems compared with 8.2–8.9 kg/ha/mm with flat-on-grade system of cultivation on Vertisols.

13.5.7.2 Rainy Season Fallow Management

Vertisols and associated soils, which occupy large areas globally (approximately 257 mha; Dudal 1965), are traditionally cultivated during postrainy season on stored soil moisture due to waterlogging-associated risks during the rainy season caused by poor infiltration rates. The practice of fallowing Vertisols and associated soils in Madhya Pradesh, India, was perceived to be decreased after the introduction of soybean; however, 2.02 mha of cultivable land is still kept fallow in central India, during the kharif season (Wani et al. 2002; Dwivedi et al. 2003). However, the survey also indicated that rainy season fallows of soybean-replaced sorghum remained fallow because rainy season crop delays the sowing of postrainy (rabi) crop, forcing the farmers to keep the cultivable lands fallow, thus reducing WUE and enhancing soil erosion. Through watershed on-farm participatory research, ICRISAT demonstrated the avoidance of waterlogging during initial crop growth periods on Vertisols by preparing the fields as BBF along with grassed waterways. Simulation studies using the SOYGRO model showed that early sowing of soybean in 7 out of 10 years was possible by which soybean yields can be increased threefold along with appropriate nutrient management. Hence, evolving timely sowing with short-duration soybean genotypes could pave the way to successful postrainy season crop where the moisture-carrying capacity is sufficiently high to support it. On-farm soybean trials conducted by ICRISAT involving improved land configuration (BBF) and short-duration soybean varieties along with fertilizer application (including micronutrients) showed a yield increase of 1300–2070 kg/ha compared with 790–1150 kg/ha in Guna, Vidisha, and Indore districts of Madhya Pradesh. Increased crop yields (40%–200%) and incomes (up to 100%) were realized with landform treatment, new varieties, and other best-bet management options (Wani et al. 2008).

13.5.7.3 Rice Fallow Management for Crop Intensification

A considerable amount of green water is available after the monsoon, especially in rice–fallow systems, which could easily be utilized by introducing a short-duration legume crop with simple seed priming and micronutrient amendments (Subbarao et al. 2001; Kumar Rao et al. 2008; Wani et al. 2009a; Singh et al. 2010). About 14.29 mha (30% of rice-growing area) rice–fallows are available in the Indo-Gangetic Plains (IGP) spread over Bangladesh, Nepal, Pakistan, and India, out of which 11.4 mha (82%) are in the states of Bihar, Madhya Pradesh, Chhattisgarh, Jharkhand, West Bengal, Orissa, and Assam in India (Subbarao et al. 2001). Taking advantage of sufficient available soil moisture in the soil after harvesting rice crop during the cool season in eastern India, growing of early maturing chickpea in rice–fallow areas with best-bet management practices (minimum tillage for chickpea, seed priming of chickpea, 4–6 h with the addition of sodium molybdate to the priming water at 0.5 g/L/kg seed and *Rhizobium* inoculation at 5 g/L/kg seed, micronutrient amendments, and use of short-duration rice cultivars during rainy season) resulted in chickpea yields of 800–850 kg/ha (Harris et al. 1999; Kumar Rao et al. 2008). An economic analysis has shown that growing legumes in rice fallows is profitable for the farmers with a B/C ratio exceeding 3.0 for many legumes. Also, utilizing rice–fallows for growing legumes could result in the generation of 584 million person-days employment for South Asia.

In a number of villages in the states of Chhattisgarh, Jharkhand, and Madhya Pradesh in India, on-farm farmers' participatory action research trials sponsored by the Ministry of Water Resources, GoI, showed significantly enhanced RUE through cultivation of rice–fallows with a total production of 5600–8500 kg/ha for two crops (rice + chickpea), benefiting the farmers with increased average net income of Indian rupees 51,000–84,000 (USD 1130–1870/ha) (Singh et al. 2010).

13.5.7.4 Soil Organic Matter Management

In addition to its importance for sustainable crop production, low soil organic matter in tropical soils is a major factor contributing to their poor productivity (Lee and Wani 1989; Bationo and Mokwunye 1991; Syers et al. 1996; Edmeades 2003; Katyal and Rattan 2003; Bationo et al. 2008; Ghosh et al. 2009; Materechera 2010). Management practices that augment soil organic matter and maintain it at a threshold level are needed. Sequestration of carbon in soil has attracted the attention of researchers and policy makers alike as an important mitigation strategy for minimizing the impacts of climate change (Velayutham et al. 2000; Lal 2004; ICRISAT 2005; Bhattacharya et al. 2009; Srinivasa Rao et al. 2009), which also serves the purpose of enhancing soil moisture storage. Agricultural soils are among the earth's largest terrestrial reservoirs of carbon and hold potential for expanded C sequestration (Lal 2004). Improved agricultural management practices in the tropics such as intercropping with legumes, horticultural crop systems, application of balanced plant nutrients, suitable land and water management, and use of stress-tolerant high-yielding cultivars improved soil organic C content and also increased crop productivity (Lee and Wani 1989; Wani et al. 1995, 2003a, 2005, 2007; ICRISAT 2005; Srinivasa Rao et al. 2009) and enhanced soil moisture storage capacity (Lee and Wani 1989; Wani et al. 1994; Pathak et al. 2005, 2009, 2011). Farm bunds and degraded common lands in the villages could be productively used for growing nitrogen (N)-fixing shrubs and trees to generate N-rich loppings. For example, growing *Gliricidia sepium* at close spacing of 75 cm on farm bunds could provide 28–30 kg N per hectare in addition to valuable organic matter (Wani et al. 2009a, 2011c). Also, through vermicomposting as a microenterprise by women self-help groups (SHGs), large quantities of farm residues and other organic wastes are converted into valuable sources of plant nutrients and organic matter, enhancing agricultural productivity (Nagavallama et al. 2005; Sreedevi et al. 2007; Wani et al. 2008; Sreedevi and Wani 2009).

13.5.7.5 Minimum Tillage or Conservation Agriculture

As mentioned earlier, there is a direct relationship between consumptive water use (ET) and crop yield. ET comprises two major processes: nonproductive evaporation and productive transpiration. Evaporation, however, cannot be avoided completely, but it can be minimized through various field-scale management practices. The three basic elements of CA are (i) no or minimal tillage without significant soil inversion, (ii) retention of crop residues on the soil surface, and (iii) growing crops in rotation appropriate to the soil–climate environment and socioeconomic conditions of the region (crop diversification). Mulching by crop residue (CA), minimal or no tillage, mixed cropping system, and practicing agroforestry are some of the examples that cover the soil surface partially and reduce evaporation. Consequently, the same amount of water could be utilized by plant transpiration, leading to more biomass and crop yield.

Conservation tillage, an essential component of CA, constitutes land cultivation techniques that try to reduce labor, promote soil fertility, and enhance soil moisture conservation. CA is now recognized as the missing link between sustainable soil management and reduced cost of labor, especially during land preparation, and holds the potential to increase crop production and reduce soil erosion. On Alfisols at ICRISAT, Yule et al. (1990) while comparing the effects of tillage (i.e., no-till, 10 cm deep till, 20 cm deep till), amendments (i.e., bare soil, rice straw mulch applied at 5 t/ha, FYM applied at 15 t/ha), and the use of perennial species (e.g., perennial pigeonpea, *Cenchrus ciliaris*, and *Stylosanthes hamata* alone or in combination) on runoff and infiltration found that straw mulch consistently reduced runoff compared with bare plots. Tillage produced variable responses in their study. Runoff was reduced for about 20 days after tillage, but the tilled plots had more runoff than no-tilled treatments during the remainder of the cropping season, suggesting some structural breakdown of the soil aggregates in the tilled plots. On an average, straw mulch and tillage increased annual infiltration by 127 and 26 mm, respectively. These results of Yule et al. (1990) indicate that mulching or keeping the soil covered (as in the case of *Stylosanthes*) should be an important component in the cropping systems of the SAT.

Studies conducted in the semiarid regions of Africa also indicate that some of the conservation tillage systems, particularly no-till techniques, give lower yield than conventional tillage methods. For example, Huxley's (1979) no-till experiments at Morogoro in Tanzania showed that no-tilled maize yielded two-thirds to three-quarters the amount of that in cultivated soil. Furthermore, Nicou and Chopart (1979) conclude in their studies in Senegal, West Africa, that in order to be effective, straw mulch in conservation tillage systems needs to be applied in sufficient quantity to cover the surface of the soil completely so that it can fully protect the soil against evaporation and runoff. It has been gaining acceptance in countries such as Tanzania, Madagascar, Zambia, and Zimbabwe in Africa (Biamah et al. 2000; Nyagumbo 2000).

Kajiru and Nkuba (2010) reported that by adopting CA techniques in Tanzania's Bukoba and Missenyi districts of Kagera region, average maize yield increased from 2.50 t/ha to 3.40 t/ha by smallholder farmers. Tanzania has been fostering the adoption of CA because of its potential to address three areas of crucial importance to smallholder farmers: demand on household labor, food security through increased and sustainable crop yields, and household income (Mariki 2004; Lofstrand 2005). Some form of CA is practiced on 40% of the rainfed farm lands in the United States and is also becoming popular in several Latin American countries (Landers et al. 2001; Derpsch 2005). Examples from SSA show that converting from plough to CA resulted in yield improvements ranging between 20% and 120%, with WP enhancement ranging from 10% to 40% (Rockström et al. 2009). On the Loess Plateau, CA increased wheat productivity and WUE by up to 35% compared with conventional tillage, especially in the low rainfall years, suggesting benefits of CA in dry farming areas of northern China (Li HongWen et al. 2007; Wang et al. 2007). For the best results, CA practices such as mulching must be accompanied by requisite agronomic practices such as use of fertilizers, manures, pesticides, and high-quality seed, as well as proper water application and management. The potential disadvantages of CA are higher costs of pests and weed control, the cost of acquiring new management skills, and investments in new planting equipment. CA can be practiced on all soils, especially light soils. It increases the productivity, sustainability, and efficient use of natural resources (Rockström et al. 2009). Straw tends to be used for animal feed in most parts of the SAT, particularly in India, Senegal, and Mali. Therefore, while mulches appear to be useful theoretically, from a practical point of view it is difficult to see how they can be used in the present conditions of SAT agriculture. It is even debatable if production of more biomass through breeding will induce farmers in the region to apply residues to their soils or induce them to sell their extra residues in view of the attractive prices offered for fodder during the dry season.

13.5.8 RUNOFF HARVESTING, GROUNDWATER RECHARGE, AND SUPPLEMENTAL IRRIGATION FOR ENHANCING RAINWATER PRODUCTIVITY

Rainfall in dry lands is highly erratic and nonuniform, which often leads to dry spells of longer duration. Various land and water interventions alleviate water stress to a certain extent, but supplemental irrigation can sometimes be extremely essential to save a crop. Crop intensification with the help of supplemental irrigation is also an important option for better use of available water resources and enhancement of income in rainfed regions.

Sharma et al. (2010) recently showed that the rainfed districts in India receiving rainfall in the range of 400–1600 mm covering 39 mha generate on an average 115 km^3/year surface runoff in a normal year. Twenty percent of harvested runoff can provide 100 mm of supplemental irrigation for 25 mha rainfed lands and the remaining 80% could contribute to meet river/environmental flow and other requirements for downstream locations. Figure 13.17 showed an average increase of 50% in total production through increased WP with one supplemental irrigation and improved management compared with the traditional practice. Several studies showed that water harvesting and supplemental irrigation are economically viable at the national level (Joshi et al. 2005, 2008; Wani et al. 2008, 2011a,b; Pathak et al. 2009, 2011; Sharma et al. 2010).

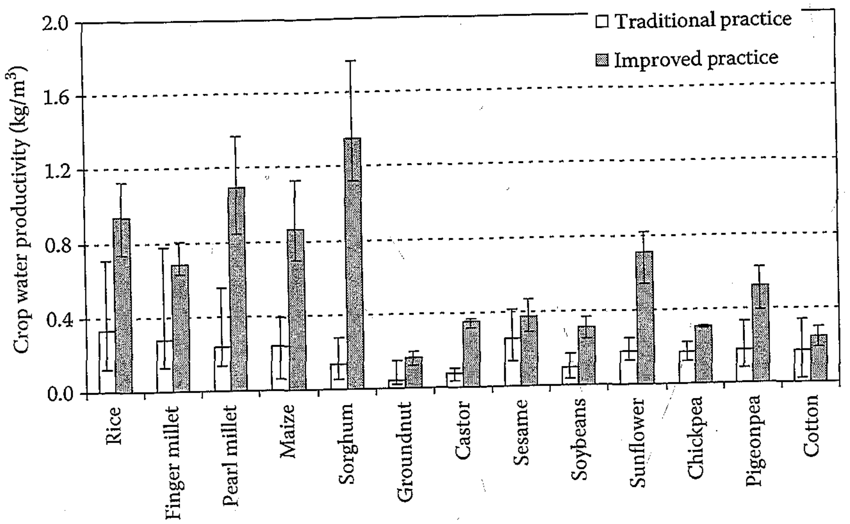

FIGURE 13.17 Crop water productivity of rainfed agriculture under traditional practices and improved technology situation in India; column in figure shows average crop yields and bars show their maximum and minimum range. (Data from Sharma, B.R., Rao, K.V., Vittal, K.P.R., et al., *Agricultural Water Management*, 97, 23–30, 2010.)

13.5.8.1 Water Harvesting and Groundwater Augmentation

RWH in watersheds is a basic activity and clear impacts of runoff harvesting through various types of structures in terms of increased groundwater availability, increased irrigated area, and increased cropping intensity are well documented in a meta-analysis result of 636 case studies reported by Joshi et al. (2008). Similar results have been also reported from a number of watersheds in India, Thailand, Vietnam, and China (Wani et al. 2003a, 2008, 2009).

13.5.9 Ex Situ Soil and Water Conservation

13.5.9.1 Runoff Harvesting and Supplemental Irrigation

The mean annual rainfall in most rainfed regions is sufficient for raising one, or in some cases, two good crops in a year. However, the onset of rainfall and its distribution are erratic, and prolonged droughts are frequent. A large part of rain occurs as high-intensity storms, resulting in sizable runoff volumes. In most rainfed regions, harvesting of excess runoff and storage into appropriate structures as well as recharging groundwater are very much feasible and a successful option for increasing and sustaining the productivity of rainfed agriculture through timely and efficient use of supplemental irrigation. In the areas with annual rainfall >500 mm, this approach could be widely adopted to enhance the cropping intensity, diversify the system into high-value crops, increase productivity and income from rainfed agriculture, and at the same time, create assets in the villages (Pathak et al. 2009, 2011; Sharma et al. 2010). Different types of runoff harvesting and groundwater-recharging structures are currently used in various regions. Some of the most commonly used structures are earthen check dams, masonry check dams, farm ponds, tanks, sunken pits, recharge pits, loose boulders, gully checks, drop structures, and percolation ponds (Figure 13.18).

Designing runoff harvesting and groundwater-recharging structures requires estimates of runoff volume, peak runoff rate, and other hydrological parameters, which are generally not available in most of the rainfed regions. Due to nonavailability of the data, many times these structures are constructed without being properly designed, resulting in higher costs and often failure of the structures. Studies conducted by ICRISAT scientists have shown that the cost of water harvesting and groundwater-recharging structures varies considerably with the types of structures (Figure 13.19a) and the selection of appropriate location. Selection of appropriate location for structures can also play a very important role in reducing the cost of the structures (Figure 13.19b).

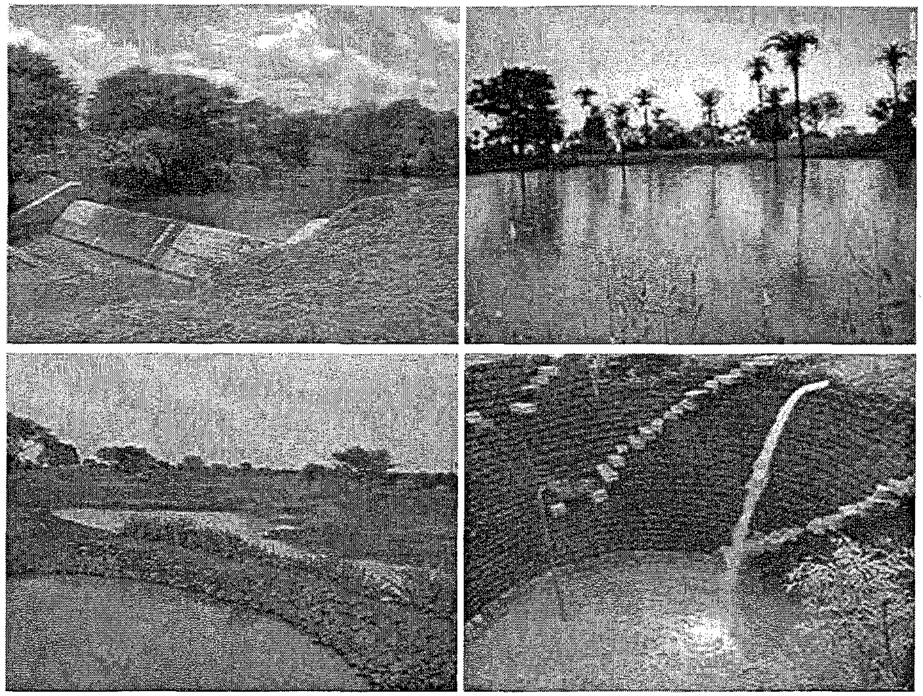

FIGURE 13.18 Commonly used water harvesting and groundwater recharging structures. (From Pathak, P., Sahrawat, K.L., Wani, S.P., et al., In *Rainfed Agriculture: Unlocking the Potential*, pp. 197–221, Comprehensive Assessment of Water Management in Agriculture Series. CAB International, Wallingford, UK, 2009.)

Pathak et al. (2009) reported that considerable information on various aspects of runoff water harvesting and supplemental irrigation could be obtained by using various models (Pathak et al. 1989; Ajay Kumar 1991), namely, runoff model, water harvesting model (Sireesha 2003), and model for optimizing the tank size (Sharma and Helweg 1982; Arnold and Stockle 1991). These models can assess the prospects of runoff water harvesting and possible benefits from irrigation. They can also be used to estimate the optimum tank size, which is very important for the success of the water-harvesting system. The information generated can also help in developing strategies for scheduling supplemental irrigation, particularly in cases where drought occurs more than once during the cropping season.

Rainfed agriculture has traditionally been managed at the field scale. Supplemental irrigation systems, with storage capacities generally in the range of 20–100 mm of irrigation water, even though small in comparison to irrigation storage, require planning and management at the catchment scale, as capturing local runoff may impact other water users and ecosystems. Legal frameworks and water rights pertaining to the collection of local surface runoff are required, as are human capacities for planning, constructing, and maintaining storage systems for supplemental irrigation, and moreover, farmers must be able to take responsibility for the operation and management of the systems. Supplemental irrigation systems also can be used in small vegetable gardens

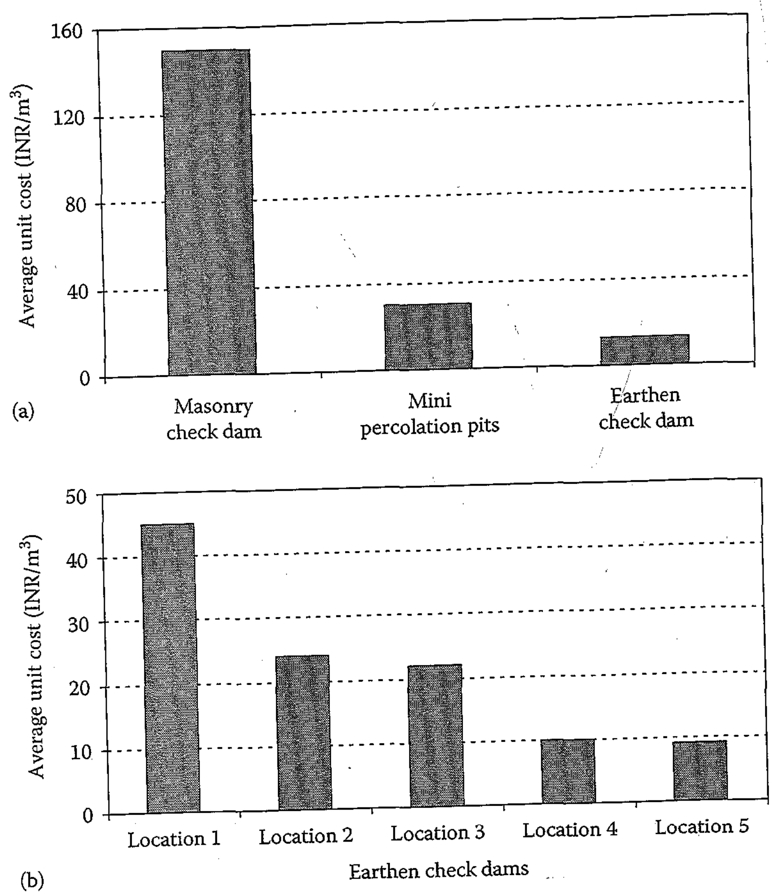

FIGURE 13.19 (a) Cost of harvesting water in different structures at Kothapally watershed, Andhra Pradesh, India. (b) Cost of water harvesting at different locations in Lalatora watershed, Madhya Pradesh, India. (From Pathak, P., Sahrawat, K.L., Wani, S.P., et al., In *Rainfed Agriculture: Unlocking the Potential*, pp. 197–221, Comprehensive Assessment of Water Management in Agriculture Series. CAB International, Wallingford, UK, 2009.)

during the dry seasons to produce fully irrigated cash crops. It is a key strategy, still underused, for unlocking the rainfed productivity potential and WP.

13.5.10 INCREASING WATER USE AND WATER-USE EFFICIENCY

13.5.10.1 Efficient Supplemental Irrigation

In the semiarid 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: 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.

13.5.10.2 Conveyance of Water to the Field

In most SAT areas, 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 0.3–1.2 mm/h (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 use of closed conduits (plastic, rubber, metallic, and cement pipes) are becoming popular, especially with farmers growing high-value crops, namely vegetables and horticultural crops (Pathak et al. 2009).

13.5.10.3 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) 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. As compared with narrow ridge and furrow, the BBF system saved 45% of the water without affecting crop yields on Vertisols. Compared with narrow ridge and furrow and flat systems, the BBF system had higher water application efficiency (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 the efficiency of water application showed that the rate of water advance was substantially higher in cultivated furrows as compared with 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.

13.5.10.4 Scheduling of Irrigation and Deficit Irrigation

Srivastava et al. (1985) studied the response of postrainy season crops to supplemental irrigation of maize or mung bean grown on a vertisol. The highest WAE was recorded for chickpea (5.6 kg/mm/ha), followed by chili (4.1 kg/mm/ha) and safflower (2.1 kg/mm/ha) (Table 13.6a). It was concluded that a single presowing irrigation to the sequential crops of chickpea and chili was profitable on Vertisols. Average additional gross returns due to supplemental irrigation were about USD 36/ha for safflower, USD 175/ha for chickpea, and USD 324/ha for chili.

Impressive benefits were 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/ha) was more than that for pearl millet (8.8–10.2 kg/mm/ha) (Table 13.6b). An intercropped pigeonpea responded less to irrigation, and the average WAE ranged from 5.3 to 6.7 kg/mm/ha 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/ha (Table 13.6b).

For the sorghum–pigeonpea intercrop, two irrigations of 40 mm each gave an additional gross return of USD 217/ha. The highest additional gross return of USD 1296/ha from supplemental irrigation was obtained with tomato.

The best responses to supplemental irrigation were obtained when irrigation water was applied at critical stages. To get the maximum benefit from the available water, growing high-value crops (namely, 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.

TABLE 13.6b
Grain Yield Response of Cropping Systems to Supplemental Irrigation on an Alfisol Watershed at ICRISAT, Patancheru, Andhra Pradesh, India, 1981–1982

Yield with Irrigation (kg/ha)	Yield Increase (kg/ha)	WAE (kg/ha mm)	Yield with Irrigations (kg/ha)	Yield Increase (kg/ha)	WAE (kg/ha mm)	Combined WAE (kg/ha mm)
Intercropping System						
	Pearl millet			pigeonpea		
2353	403	10.0	1,197	423	5.3	6.8
	Sorghum			pigeonpea		
3155	595	14.9	1,220	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	26,250	14,900	186.3	127.1

Source: Pathak, P. and Laryea, K.B., Prospects of water harvesting and its utilization for agriculture in the semi-arid tropics. In *Proceedings of the Symposium of the SADCC Land and Water Management Research Program Scientific Conference*, October 8–10, 1990, pp. 253–268. Gaborone, Botswana, 1991.

Note: Irrigation of 40 mm each was applied.

$$\text{Water Application Efficiency (WAE)} = \frac{\text{Increase in yield due to irrigation}}{\text{Amount of irrigation applied}}$$

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.

13.5.11 WATER ALONE CANNOT DO IT

Water indeed is the primary element for crop growth, but water alone cannot bring production to its potential level; balanced nutrients (macro and micro), genetically improved stress-tolerant and high-yielding cultivars, and a pest- and disease-free environment are equally important.

13.5.11.1 Balanced Plant Nutrition

Along with water scarcity, soil fertility management in particular needs to be paid due attention alongside water stress management in view of the fragile nature of the soil resource base (Wani et al. 2009a; Sahrawat et al. 2010a,b). Moreover, it is commonly believed that at relatively low yields of crops in the rainfed systems, the deficiencies of major nutrients, especially N and P, are important for the SAT soils (El-Swaify et al. 1985; Rego et al. 2003; Sharma et al. 2009), and little attention was given to diagnose the extent of deficiencies of the secondary nutrients such as S and micronutrients in various crop production systems (Rego et al. 2005; Sahrawat et al. 2007, 2010a, 2011) on millions of small and marginal farmers' fields. Since 1999, ICRISAT and its partners have been conducting systematic and detailed studies on the diagnosis and management of nutrient deficiencies in the semiarid regions of Asia with emphasis on the semiarid regions of India under the IWMP (Wani et al. 2009a). These studies revealed widespread deficiencies of multiple nutrients including micronutrients such as boron, zinc, and the secondary nutrient sulfur in 80%–100% of farmers' fields (Rego et al. 2005; Sahrawat et al. 2007, 2010b, 2011). On-farm trials conducted in several states of India (Andhra Pradesh, Madhya Pradesh, Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Jharkhand, Tamil Nadu, Chhattisgarh, and Gujarat) showed significantly increased yields by 30%–120% in different crops with amendment of soils with the deficient micronutrients and secondary nutrients over the farmers' practice, resulting in overall increase in WUE and nutrient use efficiency (Table 13.6a) (Wani et al. 2006b, 2009a, 2011c; Rego et al. 2007). For example, Singh et al. (2009, 2011) reported that the application of S, B, and Zn over the FI treatment in on-farm trials in the SAT regions of India (states of Andhra Pradesh and Madhya Pradesh) increased the productivity of rainfed crops, resulting in increased RUE. The RUE of maize for grain production under FI was 5.2 kg/mm ha water compared with 9.2 kg/mm ha water with the combined application of S, B, and Zn over the FI treatment (Table 13.6c). The best results in terms of RUE for maize and several other crops, however, were obtained under the BN treatment when N and P were added along with S, B, and Zn. These results are in agreement with those reported by Rego et al. (2007), who found that farmers were applying sub-optimum quantity of major nutrients, especially N and P, and thus the applications of NP along with SBZn (NP + SBZn) gave the best results in terms of crop yield, biomass production, and nutrient uptake.

In an on-farm study conducted for three seasons (2005–2007) in the SAT region of Karnataka, Rajashekhara Rao et al. (2010) reported that balanced nutrient application not only increased grain and stover yield of rainfed maize (see results in Table 13.6a) but also increased partial factor productivity (grain yield in fertilized plot = [grain yield in absolute control + yield increase due to treatment] × amount of nutrient applied), agronomic efficiency (the incremental efficiency of applied nutrients over the control), B/C ratio ([grain yield of fertilized plot × price of grain] : [amount of nutrient applied × price of the applied nutrient inputs]), and RUE (grain yield/rainfall received during the growing season) for maize production (Table 13.6a).

Thus, soil quality or health is a major driver of enhanced RUE and productivity in rainfed systems and needs an implementing strategy in which balanced nutrients are integrated with soil and water conservation and management (Wani et al. 2009b).

13.5.11.2 Genetically Improved Crop Cultivars

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 a mean yield advantage of 52% in finger millet was achieved with the use of high-yielding varieties such as GPU 28, MR 1, HR 911, and L 5 under farmer nutrient inputs and traditional management compared with use of local variety and farmer management. These results showed that the efficient use of available resources by the improved varieties reflected in the grain yields under given situations. However, a 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 under farmer management compared with 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 (Sreedevi and Wani 2009).

13.5.11.3 Integrated Pest Management

Introduction of IPM in cotton and pigeonpea substantially reduced the number of chemical insecticidal sprays in Kothapally, India, during the season and thus reduced the pollution of water bodies with harmful chemicals. Introduction of IPM and improved cropping systems decreased the use of pesticides worth USD 44–66/ha (Ranga Rao et al. 2007). The IPM practices, which brought into use

TABLE 13.6c
Impact of IWRM-Based Intervention on Surface Runoff, Soil Loss, Cropping Intensity and Change in Land Use at Different Benchmark Locations and Farm Fields in India and Elsewhere

Study Location/ Benchmark Site	Interventions Made	Parameter Identified/ Estimated	Before/without Interventions	After/with Interventions	Impact Achieved	Data Source
ICRISAT, Patancheru, India	Land form treatment in Alfisol	Soil loss (t/ha)	5.6	3.3	40% decreased	Pathak and Laryea (1995)
	Land form + Surface mulching	Soil loss (t/ha)	5.6	1.4	4 folds decreased	
ICRISAT Patancheru, India	Land form treatment in Vertisol	Runoff (% of rainfall received)	27	10	63% decreased	Pathak et al. (1985)
	Land form treatment in Vertisol	Soil loss (t/ha)	6.7	0.6	90% decreased	
Bellary, Karnataka, India	In situ moisture conservation practices	Water productivity (Kg/m^3)	0.73	0.84	15% increased	Patil (2003)
Bellary, Karnataka, India 1988–1996	Vegetative barrier (land slope 1.5%)	Average runoff (mm) during rainfall of 100 mm intensity	59	44	36% decreased	Rama Mohan Rao et al. (2000) and Pathak et al. (2011)
		Soil loss (t/ha)	1.6	0.9	41% decreased	
Shekta watershed, Maharashtra (MH), India	IWRM-based interventions	Waste land rehabilitation	8% of total area	Nil	Improved landscape	Sreedevi et al. (2008)
	IWRM-based interventions	Cropping intensity (%)	95	123	30% increased	Wani et al. (2011)
Watershed in Ghod catchment, MH, India (area: 1333 ha)	IWRM-based interventions	Landuse change	Wasteland: 62% Ag Land: 38% Double crop: 11%	Wasteland: 48% Ag Land: 52% Double crop: 18%	Resilient and productive land use	Wani et al. (2005)
Tad Fa, NE, Thailand	IWRM-based interventions	Runoff mm	364 (28% of rainfall)	169 (13% of rainfall)	Reduced by 54%	Wani et al. (2011)
		Soil loss (t/ha)	31.2	4.2	Decreased by 87%	
Andhra Pradesh, India	Effect of micronutrient application	Rain use efficiency (kg/ha/mm)			Increased (%)	Singh et al. (2009)
		Maize	5.2	9.2	77	
		Groundnut	1.6	2.8	75	
		Mung bean	1.7	2.9	71	
		Sorghum	1.7	3.7	118	
Madhya Pradesh, India		Soybean	1.4	2.7	93	

local knowledge of using insect traps of molasses, light traps, and tobacco waste, led to extensive vegetable production in Xiaoxingcun (China) and Wang Chai (Thailand) watersheds (Wani et al. 2006b).

13.5.12 WATER–ENERGY NEXUS

Efficient use of water for irrigation, particularly groundwater, is closely related to assured supply of power for pumping out water from wells (open and bore wells). In India, above 44% of 142 mha arable land (62 mha) is irrigated, out of which 65% (37 mha) is irrigated with groundwater from 22 million wells powered largely with electrical pump sets. Most state governments in India have subsidized or provided free electricity for running pump sets in agricultural use. However, as the large demand for power cannot be met, as rural areas face severe power cuts and receive low-quality/low-voltage power for a limited time. As a result of free/heavily subsidized and insecure supply of low-quality power, farmers adopt the practice of leaving their pumps on continually for irrigating their fields whenever power is available. This results in low WUE, as irrespective of the plants' need, fields are irrigated. Generally, farmers irrigate the soil and not the plants.

Assured power supply is very closely related with efficient use of power as well as water in the agricultural sector. In Gujarat, the government has provided separate feeders and transformers to supply good-quality, assured power supply through a scheme called "Jyoti Gram," which has shown very good results in terms of efficient use of power as well as water. Alternatively, decentralized bioenergy produced in rural areas can also power the rural pump sets to irrigate the fields as and when needed (D'Silva et al. 2004). As in many countries including India, biofuels are considered an option for addressing the energy security concerns (Achten et al. 2010a), while also responding to the challenges of climate change mitigation (Phalan 2009). Programs for stimulating complementary use of biodiesel to displace petroleum-based diesel primarily focused on biodiesel production based on nonedible oil seeds produced on marginal or degraded lands (Wani et al. 2007, 2008).

Other than agricultural land, wasteland in the watersheds has the potential to grow trees and bioenergy crops such as *Jatropha* and *Pongamia* (Sreedevi and Wani 2009; Wani et al. 2009b), which can enhance RUE and also protect the environment. A substantial wasteland area consists of degraded lands that are deteriorating due to lack of appropriate soil and water management, or due to natural causes, which can be brought into more productive use. In India, roughly 40% of the wasteland area has been estimated as available for forestation (Sathaye et al. 2001) and about 14 mha is considered suitable for cultivating biofuel feedstocks, such as *Jatropha* (Wani et al. 2009b). Establishment of biofuel plantations is considered an option for rehabilitating wastelands, enhancing energy security, and providing employment opportunities and better livelihoods in rural areas (Wani and Sreedevi 2005; Wani et al. 2006b, 2009b; Phalan 2009; Sreedevi et al. 2009b; Achten et al. 2010b). In Powerguda hamlet in Adilabad district of Andhra Pradesh, which is inhabited by indigenous people, women SHGs have achieved through collective action a feat of extracting nonedible oil from *Pongamia pinnata* seeds collected from the existing trees in the forest using their right to harvest nontimber produce from the forest. The farmers from Kistapur have used a common bore well for pumping water using *Pongamia* oil in a diesel pump set and shared the bore well water among 12 small farmers. This initiative implemented by ICRISAT was funded by the United States Agency for International Development (USAID) for enhancing WUE through assured supply of power and sharing a common bore well along with other crop productivity enhancement options (Wani et al. 2009b).

However, to assess the impact of developing degraded lands in a watershed with biodiesel plantations, Garg et al. (2011b) investigated the opportunities and trade-offs of *Jatropha* cultivation on wastelands from a livelihood and environmental perspective, with soil and water as the critical resources. The water balance for fallow wasteland and *Jatropha*-cultivated land from a site located in Andhra Pradesh, southern India, showed reduced runoff from 43% to 31% following cultivation of *Jatropha* in fallow wasteland. Correspondingly, green water consumption increased from 52% to

TABLE 13.7
Annual Water Budget of Wasteland under Two Different Land Uses during 2009 (Velchal Village, Andhra Pradesh, India)

Water Balance Component	Fallow Land	*Jatropha* Land with Land Management Practices
Rainfall (mm)	896	896
Outflow (mm)	393 (43%) Erosive runoff	274 (31%) Less erosive
E or ET (mm)	460 (52%) (nonproductive)	200 (E) + 380 (T) = 580 (64%) (productive use)
GW recharge (mm)	43 (5%)	42 (5%)

Watershed water balance: rainfall = outflow (surface runoff) + evapotranspiration (ET) + groundwater recharge

64% due to a shift from soil evaporation to crop ET without affecting the groundwater recharge in both the scenarios (Garg et al. 2011a; Yeh et al. 2011; Table 13.7).

In fallow wasteland, a large fraction of rainfall absorbed by the soil (in the form of soil moisture) was lost through soil evaporation in monsoon and nonmonsoon periods. Diversion of water from runoff and evaporation to ET led to increased plant growth. This benefited the landscape by increasing soil moisture content and reducing soil erosion and nutrient losses. Measured agronomical data show that *Jatropha* produced approximately 1–1.5 t/ha of seed biomass annually, and biomass containing 1 tC/ha per annum was added to soil during dormancy (leaf fall and pruned plant parts). Thus, *Jatropha* could be a suitable candidate for sequestering carbon and rehabilitating wasteland into productive lands with increased water-holding capacity of soil over a long time period (Wani et al. 2009b; Yeh et al. 2011). At the subbasin scale, reductions in runoff as a result of converting wastelands to biofuel plantations may pose problems for downstream ecosystems and water users if implemented on a large area; however, base flow actually improved with biofuel cropping while storm flows and sedimentation loads were lower. On the other hand, the risk from flooding and soil loss was reduced with less runoff from the upstream land. The net impact of these changes depended on the characteristics of downstream water users and ecosystems (Garg et al. 2011a).

13.5.13 WATER AUGMENTATION AND DEMAND MANAGEMENT MUST GO HAND IN HAND

Water scarcity symbolizes a situation (gap) when water is not sufficient to meet the entire demand. Water scarcity is the issue not only in dry land areas but sometimes also in higher rainfall regions (rainfall > 1500–2000 mm). Water scarcity could be physical, economical, and institutional (Rijsberman 2006); therefore, water augmentation and demand management must go together to bridge this gap.

In agriculture, timely and exact quantity of water application can enhance WP and simultaneously reduce water losses. Improved methods of irrigation application can further reduce water demand. WUE in most of the command areas are below 30% (Ray et al. 2002; Khare et al. 2007; Garg et al. 2011c). Water is lost through poor conveyance methods right from canal release to water application in the field. Excess water, however, returns to downstream or groundwater recharges, but a significant amount is also lost as unproductive evaporation losses. Infrastructure development, institutional arrangement, and appropriate water policy can help in demand management. Demand management in the domestic and industrial sectors is also important. Roof water harvesting can enhance safe and good-quality drinking water availability to the downstream user and cut the domestic water demand.

13.5.14 GRAY WATER RECYCLING FOR DEMAND MANAGEMENT

Wastewater and gray water recycling and its reuse are emerging as an integral part of demand management (Al-Jayyousi and Odeh 2003; Al-Hamaiedeh and Bino 2010). Gray water is defined as wastewater generated from domestic activities such as dish washing, laundry, and bathing, whereas black water consists of toilet water. Gray water is a large potential source of water and could be diverted for toilet flushing, irrigation in parks, school yards, golf areas, car washing, and fire protection, which can reduce freshwater demand up to 30% in cities (Christova-Boal et al. 1996; Dixon et al. 1999; Eriksson et al. 2002; Lu and Leung 2003; Al-Hamaiedeh and Bino 2010).

With rapid expansion of cities and domestic water supply, the quantity of wastewater is also increasing in the same proportion. Almost 90% of total water supplied for domestic use gets generated as wastewater, which is used for irrigation in agricultural areas located near the city and where freshwater availability is limited. Wastewater availability remains consistent throughout the years, which drives farmers to make use of wastewater. It could be utilized as irrigation source for rice, vegetable, and fodder production (Buechler and Scott 2006). Other than agriculture, the activities directly dependent on wastewater are practiced by different social groups on a small, medium, or large scale and include, for example, livestock rearing, aquaculture, and floriculture (Buechler 2004; Buechler and Scott 2006).

There are several benefits and challenges on gray water and wastewater use. Judicious use of gray water reuse in Australia has reduced freshwater demand, strain on wastewater treatment plants, and energy consumption. Aquifer recharge has improved due to increased infiltration flows from gray water use (Raschid 2004; Madungwe and Sakuringwa 2007). In Lebanon, gray water is a valuable resource for encouraging plant growth because of its higher nutrient content (Madungwe and Sakuringwa 2007). Gray water reuse in agriculture contributes significantly to the supply of fresh fruits and vegetables to urban markets in Latin America and in the Caribbean. The problem of blue green algae in sewage ponds and water reservoirs is significantly reduced by household reuse of gray water in Mexico (Madungwe and Sakuringwa 2007). Approximately 16,000 ha of land in and downstream of Hyderabad (India) is irrigated with wastewater or with a combination of wastewater and groundwater (Buechler and Devi 2005). Along the 10 km stretch of the Musi River (southern India) where wastewater from Hyderabad is disposed of, year-round employment is generated on wastewater-irrigated fields for female and male agricultural laborers to cultivate fodder grass or vegetables for sale in nearby markets or for use by their livestock (Buechler and Scott 2006). However, there are also higher risks associated with human health and the environment on use of wastewater, especially in developing countries, where rarely the wastewater is treated and large volumes of untreated wastewater are being reused in agriculture (Buechler and Scott 2006).

Wastewater is more saline due to dissolved solids originating in urban areas and concentrated further through high evaporation in arid, tropical climates. Heavy use of wastewater in agriculture may cause a salinity problem and can decrease the land productivity. Several types of grass fodder can be grown with saline wastewater; therefore this water is more likely to be used for fodder production, particularly where demand for dairy products is high (Buechler and Scott 2006). With the use of wastewater-generated products and exposure to animals, the health of the livestock can be at risk and the quality of their milk may decline, which can transfer the health risks to humans who consume the milk (Buechler and Scott 2006). Health problems can pose a serious hazard for agricultural workers due to pathogenic bacteria, viruses, and parasites present in the wastewater as well as for consumers of wastewater-irrigated produce, particularly if the produce is not cooked before it is consumed. Hookworm infections are more common in agricultural workers who go barefoot in wastewater-irrigated fields (Hoek et al. 2002; Buechler and Scott 2006). Gray water and wastewater, however, are potential sources of water but they have to be used very cautiously in different sectors.

13.5.15 LINKING SCALES THROUGH WATERSHED MANAGEMENT

Rainfed areas predominate in generating global food production and providing several ecosystem services essential for humanity. A watershed is a spatial unit containing diverse natural resources

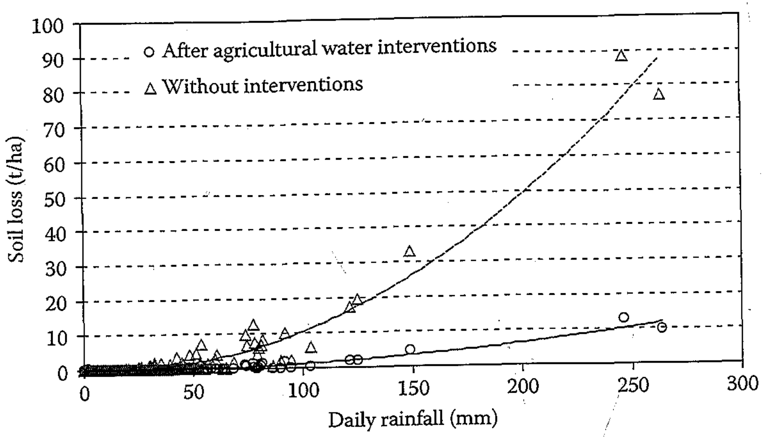

FIGURE 13.20 Impact of agricultural water interventions on soil loss in the Kothapally watershed (17°22′N latitude, 78°07′E longitude), Andhra Pradesh, India. Average annual rainfall of the study area is 850 mm.

that are unevenly distributed within a given geographical area and are ecologically complex; they are geologically and socially shared by temporal and spatial interdependence among resources and resource users (Wani et al. 2011d). The water flow (surface and subsurface) interconnects upstream and downstream areas and provides life support to people holding unequal use rights (Wani et al. 2006c). Watersheds are also inhabited by socially and economically heterogeneous groups of people located at different points along the terrain, creating potential conflicts among users of the same resources. A multitude of resources and processes that are supplied by the natural ecosystem can be strengthened by implementing IWRM. IWRM is not only helpful in enhancing the crop production and income of smallholder farmers but also in improving the water quality of groundwater wells and downstream water bodies, as well as better soil quality through C sequestration, protecting biodiversity, and minimizing soil loss. Figure 13.20 shows that soil loss was drastically reduced by implementing various water interventions in the Kothapally watershed compared with the degraded stage.

13.5.15.1 On-Site and Off-Site Impacts and Trade-Offs of Watershed Management

The principal users of the water flows are the agriculture, both rainfed and irrigated, and the ecosystem services that rely on the water quantity and quality for their functions. The IWRM approach of water management is therefore considered as an effective method in alleviating the water stress situation (Rockström et al. 2007, 2010; Rockström and Barron 2007; Wani et al. 2008, 2011b; Barron and Keys 2011). Green and blue water management at various scales not only increases food production, but has a number of social, economic, and environmental cobenefits such as protection of the environment, increase in biodiversity, and improvement in the livelihood status of local communities (Wani et al. 2003a, 2008; Rockström et al. 2007, 2010). In the IWRM approach, agricultural water interventions and in situ and ex situ practices allow more rainwater to infiltrate and enhance soil moisture (green water) and groundwater (blue water) availability. Adopting suitable cropping systems such as mixed cropping pattern (e.g., maize–pigeonpea intercropping) can enhance WP by utilizing more green water within the monsoon and postmonsoon periods.

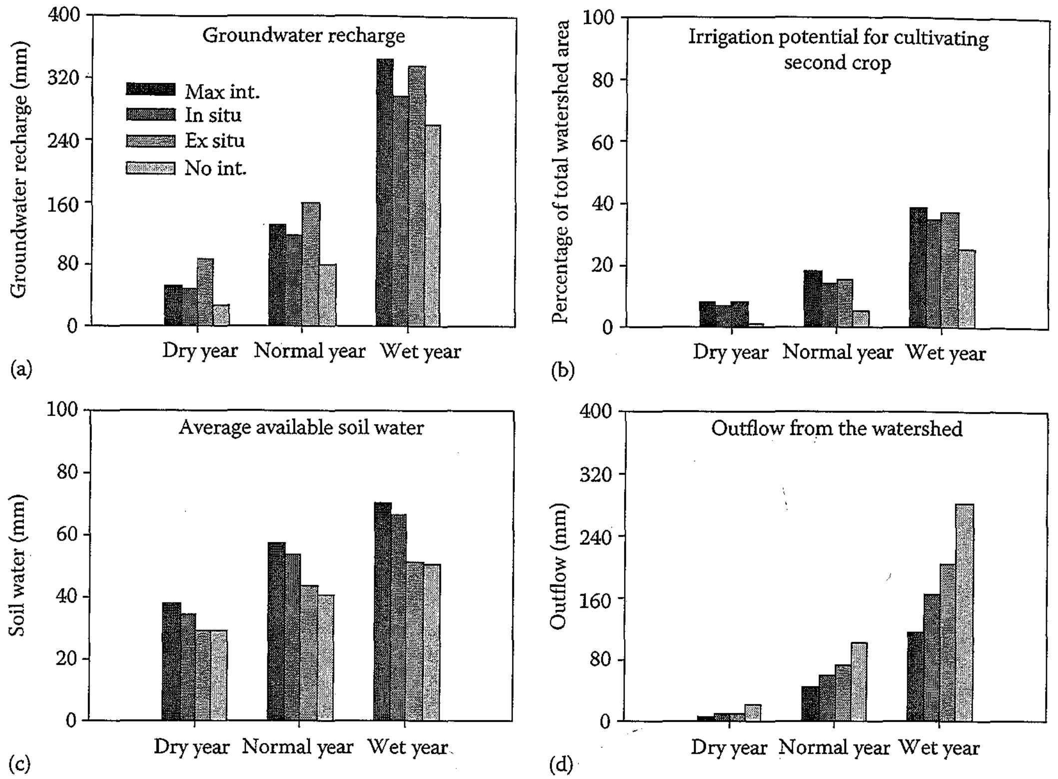

FIGURE 13.21 Comparison of (a) groundwater recharge, (b) developed irrigation potential, (c) average available soil water during crop period, and (d) outflow amount in different land management scenarios during dry, normal, and wet years.

The Kothapally watershed in Andhra Pradesh, southern India, is a classic example showing the success of IWRM where the community has moved from subsistence farming to a market-driven agriculture stage after implementation in 1999. Sreedevi et al. (2004), Wani et al. (2006b), and Garg et al. (2011a) reported that water availability and crop yield have substantially improved after the IWRM supportive interventions. Since 1999, several shallow wells that had low groundwater levels have reverted into active wells for irrigation. The cropping pattern has changed in recent years as a consequence of improved soil moisture availability and irrigation access. Farmers who were cultivating cotton of traditional varieties, sorghum, maize, paddy, onion, and chilies before the onset of the watershed development program have switched to cultivating higher-yielding cash crops such as *Bt* cotton and vegetables. Along with in situ and ex situ agricultural water management interventions, farmers have also adopted better nutrient and pest management as well as better timely operations (Sreedevi et al. 2004), which further improves agricultural productivity.

Different agricultural water interventions (shown by four scenarios) in the Kothapally watershed impact as groundwater recharge, its availability for cultivating second crop, average available soil moisture, and amount of surface runoff from watershed boundary during dry, normal, and wet years (Figure 13.21) (Garg et al. 2011a). During dry years, water management interventions became particularly important for groundwater recharge, which was more than twice as high for both ex situ and in situ interventions compared with the degraded state. Groundwater availability impacts the potential to grow a second, fully irrigated crop during the dry season (Figure 13.21b). The irrigation potential is found to have more than doubled with water management interventions during dry and normal years. In situ water management resulted in higher soil moisture availability (Figure 13.21c). Outflow varies significantly between years and with water management interventions (Figure 13.21d). Outflow was more than ten times higher during wet years compared with dry years. With maximum water interventions, outflow from the watershed was more than halved compared with the degraded state.

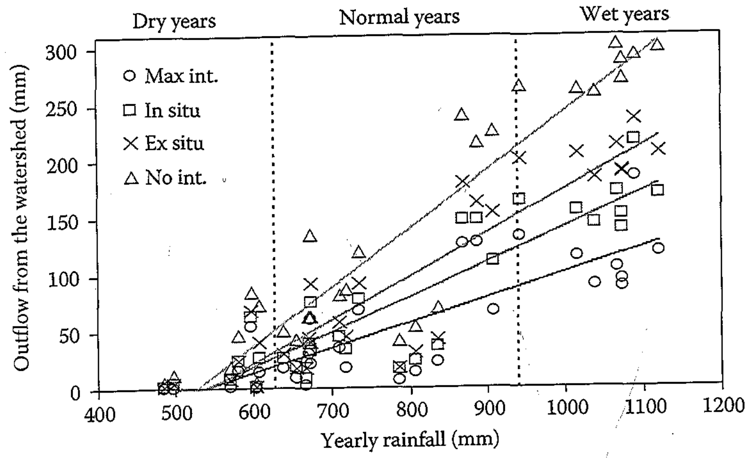

FIGURE 13.22 Rainfall–runoff relationship for the four different water management scenarios in a micro-watershed at Kothapally located in SAT, southern India. Results are based on 31 years of simulation run (SWAT, a hydrological model) from 1978 to 2008. Max int.: in situ + check-dams; In situ: in situ + no check-dams; Ex situ: no in situ + check-dams; No Int.: no in situ + no check-dams.

Figure 13.22 shows a linear relationship between the rainfall amount and the outflow of water from the watershed on a yearly time scale, but varied with water management interventions on the field scale. The lowest outflow was generated with both check dams and in situ water management in place (Max int.), while the no-interventions scenario (No int.) generated the highest outflow per rainfall event. Moreover, the results show that runoff losses were smaller for in situ management (In situ) compared with ex situ interventions (Ex situ), indicating that practicing in situ management caused larger outflow reductions from the fields than check dams in this case. This harvested amount was available in green and blue form, which helps in reducing crop water stress.

Long-term trade-off analysis on various aspects is helpful in understanding the overall benefits or losses if the IWMP program is implemented on a larger scale. It is generally assumed that IWRM does enhance water resources availability at farm and community scales at the upstream location but leads to a negative impact at downstream water bodies. It is important to analyze various ecosystem trade-offs at upstream and downstream locations before any decision making, for example, (i) increase in water resource availability, crop production, and total income developed at upstream could be compared with downstream water availability and its benefits/loss; (ii) water resource availability at upstream and downstream locations needs to be analyzed for dry, normal, and wet years; (iii) impact of soil and nutrient loss on crop production in upstream and deposition/accumulation of soil/pollutant on river beds and at downstream water bodies has to be analyzed; (iv) water quality at upstream and downstream; and (v) comparison of ecosystem services at upstream/downstream location are a matter of important concern.

Bouma et al. (2011) indicated that the capital invested under various water interventions for the Upper Musi subbasin is not remunerative and recommended the development of various infrastructures (road, school, hospital, etc.). Watershed benefits are far larger than the economic benefits, as evidence has convincingly shown that watershed development addresses the issues of minimizing land degradation, enhancing green WUE, and increasing equity for landless and women's groups and, more so, building the social capital in the rural community (Wani et al. 2003a, 2011; Bouma et al. 2011; Wilson 2011), but considering only economic returns has overlooked the issue of green WUE as well as equity concerns for the upland areas (Rockström et al. 2007, 2010; Wani et al. 2008; Kijne et al. 2009; Barron and Keys 2011).

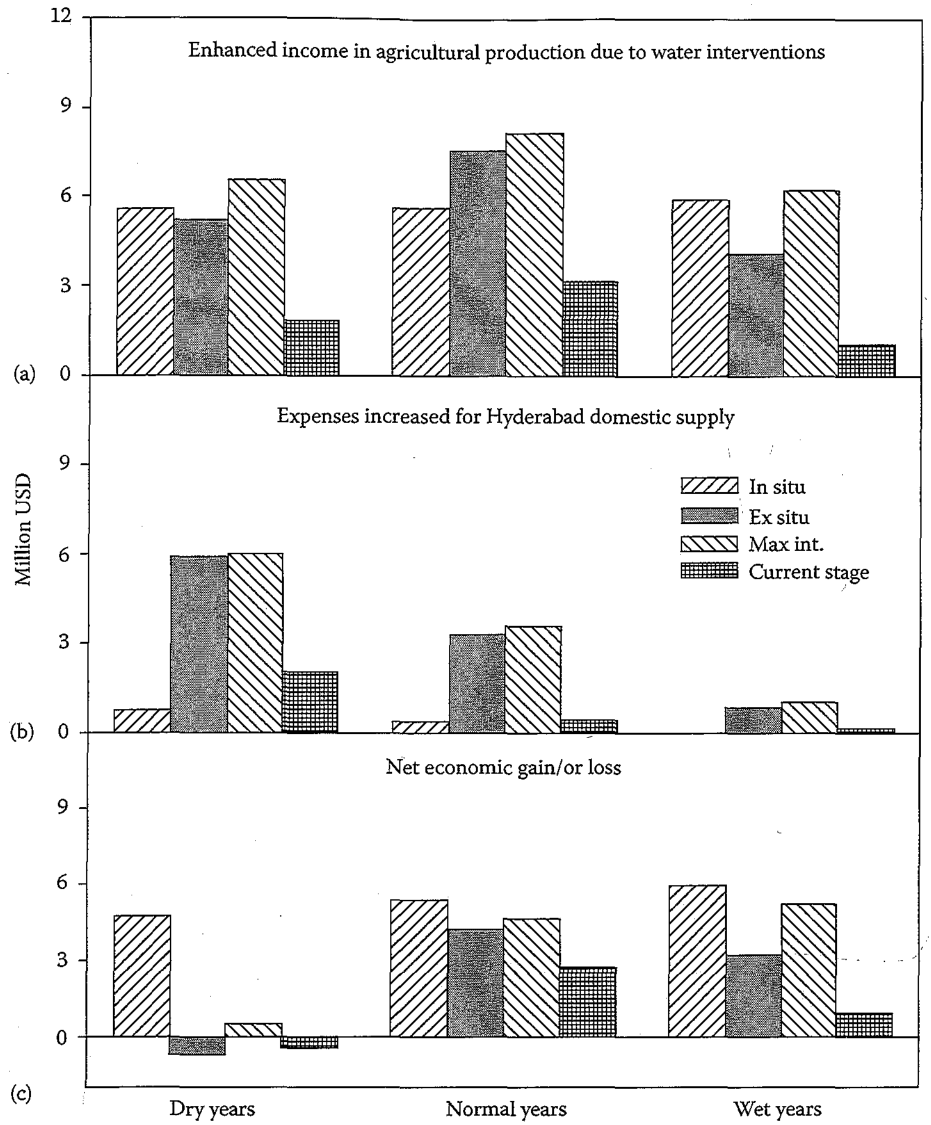

FIGURE 13.23 Trade-off analysis of (a) enhanced agricultural incomes, (b) increased costs for domestic water supply for domestic use in Hyderabad city, and (c) net economic returns/losses for three water interventions and base line scenarios compared to no interventions, under-dry, normal, and wet years.

Our analysis for the same area showed positive economic trade-offs by implementing the watershed development program in the Osman Sagar catchment area and subsequent increase in income compared with downstream water supply for Hyderabad city. It is clear from Figure 13.23 that merely by accounting the yield benefit in economic terms against the costs needed to meet water demand under varying climatic conditions, we showed a net benefit. We ascribe the differences in result to the use of an improved modeling approach more effectively representing both water and sediment flows, as well as crop yields, under varying climatic conditions (dry, normal, and wet years; Garg et al. in press). If our analyses were to include various social and environmental gains/benefits as described in the previous meta-analyses of watershed programs in India (Joshi et al. 2008; Wani et al. 2011c), the outcome of this analysis would be many more benefits in addition to economic benefits. However, as Joshi et al. (2008) concluded, there are a range of social and environmental benefits that also need to be addressed and valued for obtaining a strong case in water allocation between different users and uses in catchments and basins under watershed interventions.

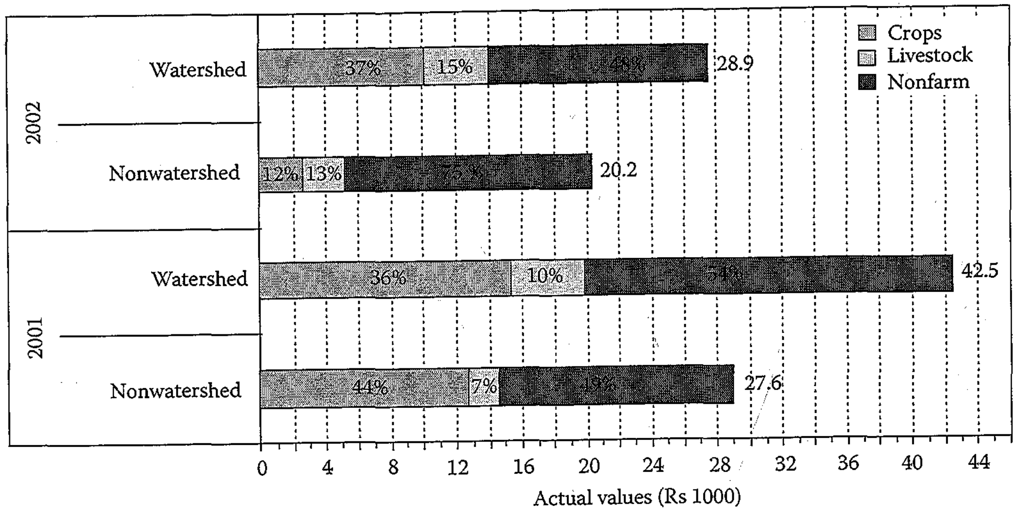

FIGURE 13.24 Income stability and resilience effects during drought year (2002) in the Adarsha watershed, Kothapally (Andhra Pradesh, India) compared to closely located nonintervention village; economic values in given figures are in Indian currency rupees (approximately 1 USD = 45 Indian rupees).

13.5.16 BUILDING RESILIENCE OF COMMUNITIES AND NATURAL RESOURCES AGAINST CLIMATE CHANGE IMPACTS

IWRM-based interventions are helpful in building resilience of natural resources and of communities against future changes including climatic variability and shocks by reducing uncertainty of crop failure and by providing better income stability (Wani et al. 2006c, 2008, 2009a; Barron and Keys 2011). Total income generated and sources of income were compared between the Adarsha watershed, Kothapally, which was transformed by IWRM-based interventions since 1999 and a nearby located nonintervention village during dry (2002) and normal rainfall years (2001). Figure 13.24 shows that average annual income of the Kothapally farmers is 45% and 55% higher than in the nonintervention village in dry and normal years, respectively, and income from crop husbandry was similar (36%–37%) to the total income in the case of the Adarsha watershed, Kothapally, during drought and normal rainfall years (showing the resilience effect of the interventions made in the watershed) (2001). However, the income from farming had drastically reduced to 12% in the nonwatershed village during the drought year (2002). During the same period (drought year), the share of income from nonfarm activities was more in nonwatershed village total income compared with that in the watershed village and people had to migrate out of nonwatershed villages in search of livelihood (Shiferaw et al. 2009).

13.5.17 OPPORTUNITIES FOR ENHANCING ECOSYSTEM SERVICES THROUGH WATERSHED MANAGEMENT

Ecosystem services were classified into four broad categories: (i) provisioning (ecosystem goods such as fuel, food, and timber); (ii) regulating (e.g., climatic regulation, pest control, and pollination); (iii) cultural (providing humans with recreational, spiritual, and aesthetic values); and (iv) supporting services (basic ecological properties/processes such as soil formation) (Millennium Ecosystem Assessment 2005; Gordon et al. 2010). Conversion of forest and woodlands into agricultural lands, however, increased the total food production to meet global food demand (provisioning ecosystem services) but at the same time led to the development of serious complications at local, regional, and global scales such as climate change, land and environmental degradation, and loss of other ecosystem services. Moreover, the feedback mechanism indicated a negative impact on agricultural productivity compared with its original stage. For example, clearing the forestland declined biodiversity, which resulted in reducing the overall pollination process (regulating ecosystem services) that is important for agriculture itself. Similarly, mass clearing of forestland increased blue water availability, which created (groundwater table) waterlogging and soil salinity, which in turn reduced the productivity of landscape and increased the risk of crop failure in Australia (Gordon et al. 2003, 2008).

A landscape that is already degraded and almost about to cross the tipping points is generally located in dryland regions. However, to rehabilitate a degraded landscape to its original state is an expensive affair, but IWRM-based interventions provide an opportunity to build, rehabilitate, and protect the ecosystem from further degradation. In this context, water management especially in agriculture plays an important role in solving some of the most pressing trade-offs between an increase in agricultural production that can contribute to food security and economic growth on the one hand, and dealing with the losses of important ecosystem benefits that also sustain human well-being and livelihoods on the other (Gordon et al. 2010). Tables 13.6a, 13.6b, and 13.6c show the impact of IWRM-based interventions on various biophysical and economic variables identified by different case studies and research findings at benchmark locations and farmers' fields in India and elsewhere. IWRM-based interventions reduced surface runoff and decreased soil loss; increased ground and surface water availability and enhanced crop yield; and increased cropping intensity and rehabilitated wastelands in a more sustainable and productive manner.

Use of fertilizers has brought major benefits to agriculture, but has also led to widespread contamination and eutrophication of surface water and groundwater (Verhoeven et al. 2006). For example, the flux of reactive N to the oceans has increased by nearly 80% between 1860 and 1990 (Millennium Ecosystem Assessment 2005). Eutrophication is usually followed by a loss of ecosystem services, such as loss of recreational values and fish production through the development of algal blooms, anoxia, and the decline of aquatic macrophytes and fisheries (Verhoeven et al. 2006; Gordon et al. 2010; Barron and Keys 2011). There are many instances where poor water management practices in agriculture have contributed to a decline in the human well-being and health (Finlayson and D'Cruz 2005; Gordon et al. 2010). Figure 13.20 shows that various agricultural water interventions reduced soil loss and runoff, which were directly associated with nitrate losses from agricultural lands (Wani et al. 2009a) by many times compared with the nonintervention stage. Similarly, it is expected that implementation of various agricultural water interventions would also help in reducing nutrient loss from agricultural fields, creating a win-win situation for both the agricultural farm at the upstream location and the water quality at the downstream level. Many water-related diseases could be successfully controlled through water management either specifically or by thoughtful approaches (e.g., watershed development) in agriculture (Coravalan et al. 2005).

Commercial agriculture has tended to favor conversion of ecosystems into monocropping (or low diversity of crops) with management focusing on a single or a few provisioning ecosystem services, such as food, timber, or fish (Gordon et al. 2010), whereas the watershed development approach promotes crop intensification along with crop diversification such as intercropping, agroforestry, floriculture by adopting various soil and water conversion measures, as well as IPM and INM practices. Such improved technologies not only maintain the productive status of the landscape but also improve the physical, chemical, and biological properties of the landscape, enhance carbon (Tables 13.5, 13.6a, 13.6b, and 13.6c) subsequently, and build system resilience against external stocks.

13.5.18 LINK ESS WITH ECONOMIC DRIVERS FOR THE COMMUNITY TO ENHANCE SUSTAINABILITY

Tangible economic benefits to all stakeholders (community in case of watersheds) are a must for community participation, which is the primary pillar of sustainability (Wani et al. 2002, 2006c, 2009a). Sustainability of watershed interventions is an important issue (Pangare 1998; Kerr et al.

2002; Wani et al. 2002, 2006, 2008,), and several assessment studies have highlighted an urgent need for improving sustainability through economic benefits. The economic drivers play an important role as they involve people in generating revenue to sustain their livelihood. The urban migration to seek jobs, especially when income and livelihood opportunities in agriculture are not sufficient to fulfill their family needs, is a typical example of this. Implementing watershed development programs enhances provisioning ecosystem services (e.g., crop, fodder, wood production) and could be linked with higher economic gain. In addition to the on-site services, there are a number of off-site ecosystem services such as reducing flooding, siltation of downstream water bodies, as well as reduced eutrophication of water bodies, improved groundwater availability, water quality, and carbon sequestration. The environmental trade-off could be directly or indirectly beneficial at both upstream and downstream locations.

Participatory biodiversity conservation enables the poor to manage their natural resources better. In Govardhanpura and Gokulpura villages in Bundi district of eastern Rajasthan, India, a participatory community initiative regenerated half of the degraded common pool resources or grazing area by adopting appropriate social and biophysical interventions. This ensured the availability of fodder for all households and an income of USD 1670 annually for the SHGs through the sale of surplus grass to surrounding villages, as for villagers in the watershed, grass on a cut-and-carry system was available freely. In Thanh Ha watershed, Vietnam, the introduction of legumes saw a jump in crop diversity factor from 0.25 in 1998 to 0.6 in 2002. In Kothapally watershed in Andhra Pradesh, India, farmers now grow 22 crops in a season with a shift in cropping pattern from cotton to a maize/pigeonpea intercrop system. More legumes are now grown in Vietnam and Thailand, reducing the need for fertilizer N (Wani et al. 2006c). Similarly, converting wasteland into *Jatropha*-cultivating land in Velchal village provided an additional source of income for marginal and landless laborers (Wani et al. 2006a,b) and also showed positive soil and hydrological trade-offs (Garg et al. 2011b).

There is a need for developing a mechanism for monitoring ESS to ensure that ESS providers from upland areas are rewarded suitably to enhance sustainability of watersheds. Benefit of the ecosystem services for individual farmer/community is relatively dependent on their socioeconomic factors and access to that service. Valuation of ecosystem services is a cumbersome task due to complex and nonlinear relationships among various interventions and ecosystem responses. However, identification and valuation of ecosystem services are important and is a challenging but essential task. There is a need to develop assessment methods, valuation, institutional mechanisms, and financial instruments.

13.5.19 EMPOWERING WOMEN AS WATER RESOURCE MANAGERS

Women constitute more than 50% of the world's population and 550 million women live below the poverty line as reported by the World Food Program. Two-thirds of the illiterates in the world are women, without any property rights, and have no economic independence (70% of the world's poor are women) (UNEP 1997). According to the "Draft National Policy for Women in Agriculture (2008)" in India, women constitute 40% of the agricultural workforce and this share is increasing. Currently, 53% of all male workers are in agriculture, while 75% of all female workers and 85% of all rural female workers are in agriculture. Women as economic income providers, caregivers, and household managers are responsible for ensuring that their families have basic resources for daily living. They are often the managers of community natural resources and have learned to protect these resources in order to preserve them for future generations (managers of sustainability) (ecosystem service providers). Although women play a pivotal role in agriculture development, more than 55% of female agricultural workers are considered laborers rather than being the owners themselves, even when their family owns land. Participation of women and resource-poor individuals is of paramount importance for the effective implementation of IWRM programs, so that they become effective vehicles for the integrated development of communities and sustainable impacts and continuing ecosystem services. In drought-prone rainfed areas, watersheds are recognized as growth engines for agricultural as well as overall development to achieve food security (Wani et al. 2008). Community participation is an important aspect of watershed development programs, and it is necessary to include equity and gender parity into the program design itself. Inclusion of women and those who are resource-poor is of paramount importance for watershed development to become truly participatory in both implementation and impact (Sreedevi et al. 2009a). Creating awareness about IWRM and water management is important among women groups and could be achieved with capacity building and women empowerment. New watershed common guidelines include microenterprises for generating income for women (GoI 2008) as the economic security/independence is already associated with the decision-making power in the house and community (Sreedevi et al. 2009a; Wani et al. 2009a).

13.5.20 PUBLIC–PRIVATE PEOPLE-CENTRIC PARTNERSHIP FOR WATER MANAGEMENT

With the basic objective of improving rural livelihoods through sustainable management of natural resources in the watersheds, it is imperative that watersheds produce marketable surplus to come out of the subsistence agriculture. To achieve the tangible economic benefits through increased productivity and diversification with high-value crops, there is a need to adopt and operationalize a holistic approach through convergence and collective action (Wani et al. 2003a, 2009a). To achieve the goal of sustainable intensification, as indicated earlier, water alone cannot do the job and it needs backward and forward linkages in terms of providing necessary inputs (seeds, fertilizers, pesticides, machineries, credit and insurance, etc.) and for value addition and linking farmers to the markets to enhance income and agricultural productivity in rural areas. There is ample space and scope to bring in public–private partnership in the consortium (Wani et al. 2006b, 2008, 2011b). For example, widespread deficiencies of micronutrients in the soils of farmers' fields were recorded and once the benefits of soil test–based applications were demonstrated, farmers were in need of the fertilizer formulations containing micronutrients as well as seeds of improved cultivars in their region.

The issue of availability of boron and other micronutrients in remote villages was resolved for thousands of farmers in different villages by building partnership with Borax Morarji Limited, a producer of B fertilizer in India as the consortium partner to link with SHGs and farmers' cooperatives. Adarsha watershed in Kothapally serves as an example of livestock-based microenterprises. Once the milk production in the village increased through animal breed improvement activity and improved/increased fodder availability, Reliance Company came forward to establish a milk procurement center in the village to buy the marketable surplus quantity. It also provided technical support and inputs for animal feed and health for ensuring increased milk production. The public–private partnership in the area of IWMP is also envisaged in the new common watershed guidelines (GoI 2008). A pilot program of public–private partnership for IWMP has been initiated in Madhya Pradesh; earlier, in Rajasthan, Indian Tobacco Company (ITC) had joined hands with the Government of Rajasthan to develop watersheds through public–private partnership in the consortium. ICRISAT has worked with Confederation of Indian Industry (CII) with other corporates such as Coca-Cola, SAB Miller in Rajasthan, Andhra Pradesh, and Karnataka to address the issues of water conservation and enhancing agricultural productivity through sustainable intensification and diversification with high-value crops. There are a number of isolated examples of public–private partnership in various areas of IWMP. For example, GIZ (GTZ), Southern Online Bio-Technology (SBT), and ICRISAT had a public–private partnership project under which SBT operated a 40 kl/day biodiesel plant in Nalgonda district, Andhra Pradesh, with German technology provided by Lurgi and ICRISAT provided technical support to the farmers for cultivating biodiesel plantations and facilitating buyback arrangements between the farmers and SBT (Kashyap 2007). A public–private partnership has to be a win-win proposition for the industries/corporate houses as well as the implementing agencies of the IWMP and the farmers, which is possible through a business model of watershed development. In addition, a number of corporates such as Sir Dorabji Tata Trust

(SDTT, Mumbai), Sir Ratan Tata Trust (SRTT, Mumbai), TVS Foundation (Chennai), Coca-Cola Foundation (United States and India), SAB Miller, India Cements Limited, and their formal associations such as Confederation of Indian Industries (CII) and Federation of Indian Chambers and Commerce Industries (FICCI) are collaborating with the ICRISAT-led consortium for fulfilling their corporate social responsibility mandate. However, to make public–private partnership a norm rather than an exception, there is a need to promote public–private partnership for harnessing the full potential of rainfed agriculture for improving rural livelihoods through sustainable management of natural resources and through enabling policies and institutional arrangements.

13.5.21 Awareness Building among All Stakeholders

Creating awareness among all the stakeholders starting from policy makers, researchers, extension officers to the end users–farmers is important. The stakeholders may collectively derive some synergetic benefits from being able to integrate their efforts. Effective participation and collective action in resource management, however, depend on the degree of awareness of important technical considerations. This awareness is possible with capacity-building programs and knowledge dissemination at every level. IWRM requires multiple interventions that jointly enhance the resource base and livelihoods of rural people. Capacity building is a process to strengthen the abilities of people to make effective and efficient use of resources in order to achieve their own goals on a sustainable basis (Wani et al. 2008). Awareness-building programs ranging from seminars, workshops, training programs to one-to-one interaction on a regular basis are required at different stakeholder group levels. Demonstration of advanced irrigation techniques such as drip and sprinklers have to be conducted on farmers' fields. Awareness-building programs on water-related issues such as groundwater augmentation and its proper utilization are helpful for long-term sustainability of water resources at the community/village scale.

13.5.22 Enabling Policies and Institutions for IWRM in Rainfed Areas

Rising demand for food and environmental water supplies presents a challenge to prevailing institutional arrangements governing freshwater access and use. With increasing water scarcity and food demand challenging the development paradigm, right policies and institutional arrangements are essential at various levels to ensure efficient management of resources. For example, in India, the focus primarily was on augmenting blue water resources. However, the GoI realized the importance of rainfed areas and therefore made significant investments (USD 6 billion until 2006) on watershed development programs at the national level since the 1970s (Wani et al. 2008). Initially, the watershed development program in India was mainly oriented toward constructing water-harvesting structures for soil and water conservation and some productivity enhancement. Subsequently, policies and institutional arrangements were modified as per the needs of the changing development scenario through lessons learned from past experiences, and observations are currently aimed at the holistic development of the rural community where watershed management is considered an entry point for improving livelihoods of people through natural resource management. However, a huge scope still exists for water management in rainfed and fallow wastelands, which requires further policy support.

Energy subsidy for tubewell irrigation in India enhanced groundwater use many times (approximately 240–260 km^3 per year in 2000) compared to the 1950s level (10–12 km^3) (Shah et al. 2005). Rural India at present uses subsidized energy worth an equivalent of USD 4.5–5.0 billion per year to pump almost 150 km^3 of water for agricultural use. Groundwater management is also a major concern for achieving sustainable development. The Ministry of Water Resources, GoI, debated the groundwater bill (control and regulation) in 1970 and revalidated it in 1992 to regulate and control the overexploitation of groundwater. The bill was circulated to all state governments to prepare similar bills to keep a check on groundwater overexploitation because water is a state subject (Singh 1995). However, as of today, only a few states have regularized groundwater bills, as the remaining states have not implemented it due to various economic and political reasons. Electric supply and pricing policy, however, offer a powerful tool for groundwater management indirectly, but most state governments are unable to implement it due to stiff resistance from farmers' groups. As the free power supply or subsidized power supply drives the groundwater exploitation movement in the country, there are a few examples of policy changes that exemplify a break from the traditional vote bank-oriented policies to ensure sustainable management of resources by taking users into confidence. The "Jyotigram scheme" is one such scheme of the Government of Gujarat, India, which is an example of comanagement of electric power and sustainable groundwater use by implementing the right policy targeting rural people. Rather than supplying free but poor-quality electric power, the Government of Gujarat, introduced (i) 24 h three-phase power supply for domestic and village industries, all subjected to metered tariff; and (ii) 8 h good-quality (uninterrupted, full voltage) assured power supply for running tube wells for agriculture use in 2003. This reduced unwanted groundwater pumping and improved the life quality of village people and their economic status (Shah and Verma 2008).

13.6 WAY FORWARD FOR IMPROVING SUSTAINABLE MANAGEMENT OF WATER RESOURCES IN THE TROPICAL REGIONS

As discussed in an earlier section, rainfed agriculture holds a huge potential to meet the future food demand. In order to achieve these targets, IWRM is the promising framework for managing water and natural resources effectively. To meet the challenges of the twenty-first century for producing more food from limited finite water and land resources, there is an urgent need to bring in a shift in managing agricultural water in the world, particularly so in the developing world. Traditionally, water management dealt with irrigated agriculture; however, as shown by the comprehensive assessment of water for food and water for life (Molden et al. 2007), agricultural water management has a wider meaning than just irrigation and the vast untapped potential of 1.2 billion hectares of rainfed agriculture needs to be harvested (Rockström et al. 2007; Wani et al. 2009a). For harnessing the potential of rainfed agriculture, the large portion of green water that is underutilized at present needs to be improved substantially. The shift in water vapor from croplands from nonproductive evaporation loss to productive ET needs to be improved, and a large scope exists for enhancing green WUE from 30%–35% to 65%–95% in rainfed areas. Appropriate policy and institutional support to decentralized water management in rainfed areas are the urgent need. Increased investments and credit support for the small and marginal farmer are required, to shift them from growing low-value crops to high-value crops through inclusive market-oriented development (IMOD).

In the initial stage of IMOD, small and marginal farmers will need incentives and enabling policies and institutions to slowly innovate to produce marketable surplus and invest further in sustainable intensification so that they can grow and prosper by intensifying rainfed agriculture. The weak link between the research and development organizations—the farmers—needs to be strengthened for efficient knowledge/technology transfer.

Use of new ICT tools not only as a means of knowledge exchange but also as a source of livelihood for the educated youth in the rural areas has to be worked out. There exists a large space for public–private partnership in the area of agricultural water management in developing countries. However, it has to be a win-win proposition for all the stakeholders/partners. Small and marginal farmers' interests must be at the center while devising public–private partnership policies. However, the operationalization of an integrated holistic strategy through a consortium approach calls for a change in the mindset of the various actors such as researchers, policy makers and development workers, farmers, and private industries.

Currently, most of the players feel comfortable while working in their own compartments/silos and there is a reluctance to work together for achieving the common goal of improving livelihoods of small and marginal farmers. However, successful examples such as the consortium approach for watershed management in Asia, developed and adopted by ICRISAT, National Agricultural Innovation Project (NAIP) of Indian Council of Agricultural Research (ICAR), GoI, as well as the Bhoochetana initiative of Government of Karnataka with the ICRISAT-led consortium, have shown very good results, and the various actors are realizing the benefits of working together in a holistic manner for a win-win proposition, which could become a powerful trigger to an operationalized holistic IWRM framework to harness the vast untapped potential of rainfed agriculture in developing countries.

ABBREVIATIONS

B/C ratio	Benefit–cost ratio
BBF	Broad bed and furrow
CA	Conservation agriculture
EA	East Asia
ET	Evapotranspiration
FAO	Food and Agriculture Program of the United Nations
FYM	Farmyard manure
GoI	Government of India
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICT	Information and Communication Technology
IGP	Indo-Gangetic Plains
IMOD	Inclusive market-oriented development
INM	Integrated nutrient management
IPM	Integrated pest management
IRR	Internal rate of return
IWMP	Integrated Watershed Management Programs
IWRM	Integrated Water Resource Management
M&E	Monitoring and evaluation
MA	Millennium Ecosystem Assessment
MDG	Millennium Development Goal
MENA	Middle East North Africa
NSG	National Support Group
PR&D	Participatory Research and Development
RUE	Rainfall use efficiency
RWH	Rainwater harvesting
S, B, and Zn	Sulfur, boron, and zinc
SA	South Asia
SAT	Semiarid tropics
SHG	Self-help group
SSA	Sub-Saharan Africa
T/ET	Transpiration to evapotranspiration ratio
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USAID	U.S. Agency for International Development
WAE	Water application efficiency
WP	Water productivity
WUE	Water-use efficiency

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14 Manipulating Crop Geometries to Increase Yields in Dryland Areas

B.A. Stewart and Rattan Lal

CONTENTS

14.1 INTRODUCTION

Drylands comprise regions characterized by different moisture regimes on the basis of the rainfall received. A region is termed hyperarid if the annual rainfall is <200 mm, arid if <200 mm during winter and <400 mm during summer, semiarid if 200–500 mm during winter and 400–600 mm during summer, and dry subhumid if 500–700 mm during winter and 600–800 mm during summer (FAO 1993). On the basis of the length of the growing season, considering favorable water balance and temperature regime, a region is categorized arid if the growing season is <75 days, semiarid if 75–120 days, and dry subhumid if 120–150 days (FAO 1993). These regions are also classified on the basis of the aridity index (AI), defined as the ratio of precipitation (P) to potential evapotranspiration (PET). The region is termed hyperarid if AI is <0.05, arid if 0.05–0.2, semiarid if 0.2–0.5, and dry subhumid if 0.5–0.65. Globally, these regions occupy 1.96 billion hectares (Bha) in Africa, 1.95 Bha in Asia, 0.66 Bha in Australasia, 0.3 Bha in Europe, 0.74 Bha in North America, and 0.54 Bha in South America (Table 14.1). Thus, drylands occupy a total of 6.15 Bha or 47.1% of the earth's land area. Principal soils consist of Aridisols (2.1 Bha), Entisols (2.3 Bha), and Alfisols (0.38 Bha) (Table 14.2). Most soils (except Vertisols and Mollisols) are coarse-textured and low in soil organic matter content and inherent soil fertility. Drought stress, low nutrient reserves, and susceptibility to erosion (by water and wind) and secondary salinization are principal soil-related constraints to achieving high biomass production and agronomic yields.

During the past 50 years, world cereal production increased about 2.7 times compared to 2.3 times for world population. This increased production was a remarkable achievement and the result of many factors. However, increased irrigated areas and increased use of chemical fertilizers are clearly two of the most important reasons. Irrigated areas more than doubled and fertilizer consumption increased several fold. Irrigated lands and favorable rainfed areas benefitted greatly