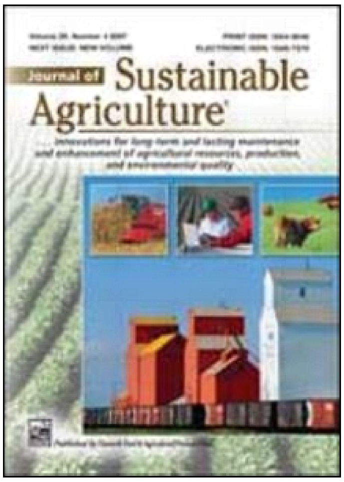

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Managing Soil Water to Improve Rainfed Agriculture in India

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Managing Soil Water to Improve Rainfed Agriculture in India

Rattan Lal

ABSTRACT. Rainfed agriculture is practiced on two-thirds of the total cropland area of 162 million hectares (Mha) in India. While yield and total productivity of irrigated crops have improved since the 1960s, those of rainfed crops or dry farming have stagnated. Yet, the average crop yield under rainfed conditions in research and demonstration plots is two to four times higher than the national average crop yields. Low crop yields under rainfed conditions are due to recurring drought stress, high soil temperatures, widespread soil degradation and desertification, and poor management. Soil-related constraints that exacerbate drought stress include crusting and compaction, low water infiltration rate, low water retention capacity, high surface runoff, and high losses due to soil evaporation. India receives about 400×10^6 ha-m of rainfall annually, most of which is received in 100 hours over a span of 25 nonconsecutive rain days. Thus, 45% (or 180×10^6 ha-m) is lost as runoff or *blue water*. Some of the water stored in soil as *green water* is lost by soil evaporation, and the productive *green water* used as direct transpiration is rather small. Impedance to deep root penetration due to high bulk density, low porosity, and hard-setting are among important factors responsible for low fraction of "productive *green water*." Recommended management practices (RMPs) that conserve water in the root zone and increase water use efficiency (WUE) are: (i) plowing of deep compacted soils with massive structure and low porosity, (ii) using a minimum or no-till system in light-textured soils with favorable structure,

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(iii) mulching with crop residues, other biosolids, and synthetic polymers, (iv) harvesting runoff water and recycling it for supplemental irrigation, and (v) adopting integrated farming systems involving legume-based rotations and agroforestry measures, which reduce water runoff and improve soil fertility. Available research results suggest a large potential for improving productivity through adoption of site-specific RMPs. Thus, there is a strong need to validate RMPs on benchmark soils in diverse agroecoregions of India, under on-farm conditions and with farmer participation, to facilitate widespread adoption.

KEYWORDS. Dry farming, water harvesting, water conservation, drought, high soil temperatures, Indian agriculture, irrigation

INTRODUCTION

India is a large and ecologically diverse country. Of the 21 distinct agro-ecological regions, at least 11 agro-ecoregions are characterized as cold arid, hot arid, dry semi-arid, semi-arid, and dry sub-humid climates. These ecoregions are especially prone to water shortages and recurring drought. In addition, 66% of the cropland area in India is rainfed, in which crop yields depend on the rainfall amount and its distribution, and more importantly, on its effective utilization. Despite impressive gains in food production through adoption of so-called Green Revolution technologies (Evenson and Gallin, 2003), even greater challenges lie ahead in improving productivity of rainfed crops. Annual food grain production in India includes 85.3 million Mg of rice grown on 42.5 Mha, and 72 million Mg of wheat grown on 26.6 Mha (Annonymous, 2004, 2005). In the recent years, however, grain production has not kept pace with the increasing population of about 1.1 billion. For the first time in several years, India imported wheat in 2006 to replenish its alarmingly low grain reserves and to contain the inflation rate (Rai, 2006). The expected food grain demand (amounts million Mg) for medium and high dietary requirements, respectively, are 253 and 315 in 2011, 308 and 385 in 2021, and 338 and 423 in 2025, respectively (Sekhon, 1997). Principal constraints to achieving these production targets are lack of adequate water, recurring drought stress, low water use efficiency, and lack of adoption of recommended management practices (RMPs) in rainfed agriculture. These constraints are exacerbated by soil degradation, which is a serious problem in India (FAO, 1994). India's success in achieving the required agricultural production targets depends on its ability to conserve, manage, and recycle water resources. Irrigated agriculture has made a major impact on agronomic production. Of the arable land area in India of 162 Mha, about one-third is irrigated. Irrigated land area in India has increased substantially since the 1970s and was 33.7 Mha in 1975, 41.8 Mha in 1985, 50.1 Mha in 1995, 54.8 Mha in 1998, and 55.8 Mha in 2003. Cereal production in India increased from 80 million Mg with irrigated cropland area of 25 Mha to 230 million Mg with irrigated cropland area of 56 Mha, at an average rate of growth of 4.8 Mg ha^{-1} yr^{-1} of irrigated cropland. However, any further expansion of irrigation in India is difficult, and not without severe negative economic, environmental, social, and political consequences (Droogers et al., 2001). Water availability for agriculture in India is facing strong competition from urbanization and rapid industrial development. Thus, any future increase in agricultural production in India will have to come through improvements in rainfed agriculture, which is subject to the vagaries of monsoon, high soil evaporation rates, and harsh tropical climate. Therefore, the objective of this manuscript is to describe processes and practices of managing, conserving, and recycling rain water for enhancing agronomic production of crops grown under rainfed or dry-faming conditions in India.

WATER RESOURCES OF INDIA

Renewable water resources are limited on the global scale and are also vulnerable to the projected climate change (Vörösmarty et al., 2000). India is endowed with large renewable water resources, but is faced with the issue of imbalance, poor seasonal distribution, and vulnerability to changing climates. As much as 139 Mha of land area receives > 1000 mm yr^{-1}, of which 33 Mha receives > 2500 mm yr^{-1} of rainfall (Table 1). Total annual rainfall received in India is about 400 million ha-m (Table 1). Of this, only 150 million ha-m (37.5%) infiltrates into the soil, 180 million ha-m (45%) is lost as surface runoff, and 17.5% as evaporation (Bhaskar, 2002). Therefore, conservation, management, and recycling of rain water are crucial to reducing waste and to enhancing production of rainfed agriculture. Drought management is an important strategy to enhancing production from rainfed arriculture in India (Rai, 2004).

Annual internal and external renewable water resources of India are estimated at 2085 km^3 (Table 2). Per capita internal water resources in 2006 are estimated at 1666 m^3. However, the annual withdrawal of water

TABLE 1. Rainfall received in different geographical regions of India (Bhaskar, 2002)

Rainfall (mm/yr^{-1})	Geographical Area (10^6 ha)	Rainwater Received (10^6 ha-m)
100–500	52.1	15.6
500–750	40.3	25.2
750–1000	65.9	57.6
1000–2500	106.4	205.9
> 2500	32.6	95.7
Total	297.3	400

TABLE 2. Water resources of India (Recalculated from Kaosa-ard and Rerkasem, 2000)

Parameter	Value	Units
1. Annual internal renewable water resources	1850	km^3
2. Per capita internal water resources (2006)	1666	km^3
3. Annual river flow from external sources	235	km^3
4. Annual withdrawal of water		km^3
(i) Volume	380	km^3
(ii) Per capita withdrawal (2006)	537	m^3
(iii) Proportion of internal resources	20.54	%
(iv) Proportion of total resources	18.23	%

Note: Values in Item No. 2 and 4 (i) are based on an estimated 2006 population of 1078 million.

is high. India uses 200 km^3 yr^{-1} of water for irrigation, which is three times the flow of water in China's Yellow river, and the use efficiency is hardly 20% to 30%. Use of irrigation water in India is excessive, wasteful, and detrimental to soil because of the risk for a falling water table with tube well irrigation, a rising water table with canal irrigation, and salinization because of poor-quality water. Because of the drastic increase in population, per capita availability of fresh water resources in India declined from 6000 m^3 yr^{-1} in 1947 to 2,260 m^3 yr^{-1} in 1997, and is expected to decline to only 1,130 m^3 yr^{-1} by 2047 (Table 3). While the average per capita available water supply will remain adequate until the population stabilizes around 1.6 billion, population in arid and semi-arid regions is prone to water shortages during the prolonged dry periods. The water scarcity will be aggravated by the shrinking snow/ice mass in the

TABLE 3. Per capita availability of fresh water resources in India (Recalculated from Engelman and LeRoy, 1993)

Year	Per capita water availability ($10^3 m^3$) yr^{-1}
1947	6.00
1957	5.32
1967	4.24
1977	3.39
1987	2.74
1997	2.26
2007	1.95
2017	1.68
2027	1.50
2037	1.21
2047	1.13

Himalayas because of global warming. Major rivers of India (and others in Asia such as the Yangtze, Mekong) originate from the Himalayas. Shrinkage of ice mass may alter the hydrology, increasing runoff during the rainy season and reducing or eliminating flow during the dry season (Brown, 2001).

SOIL RESOURCES OF INDIA

In accord with the diversity of agro-ecological regions, India's soils are equally diverse. Predominant soils of India include Alfisols (68.9 Mha), Inceptisols (63.8 Mha), Vertisols (60.3 Mha), Ultisols (36.6 Mha), Entisols (24.7 Mha), Aridisols (18.3 Mha) Mollisols (17.8 Mha), shifting sands (14.3 Mha), Histosols (0.8 Mha), and others (7.8 Mha) (Eswaran et al., 1999). These diverse soils are of varying land quality (capability) classes (Table 4). Soils with no or few constraints cover a land area of about 15 Mha, and those with moderate constraints (high temperature, low soil organic matter content, cracking, etc.) occupy 90 Mha. The land area of soils with low fertility and susceptibility to drought stress and nutrient imbalance is estimated at 104 Mha. Thus, about 125 Mha of land areas (under land quality classes of II to VI) are prone to soil-related constraints including drought stress, high temperatures, and nutrient imbalance, (Table 4). It is these soils that are in need of sustainable management through adoption of RMPs aimed at improving WUE and increasing crop yields.

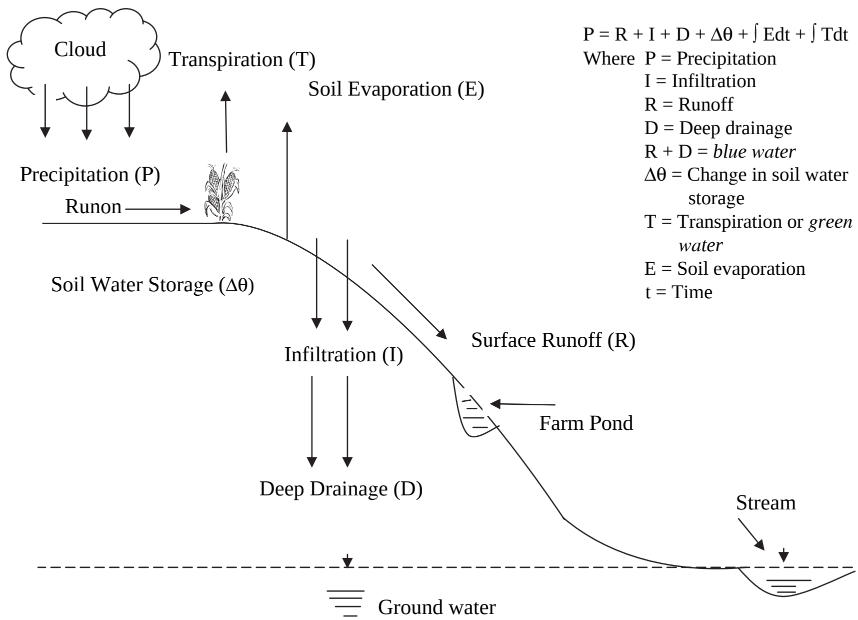
TABLE 4. Areas under different land quality classes in India and the population carrying capacity at low input levels (Modified from Beinroth et al., 2001)

Land Quality Class.	Characteristics	Area (10^6 ha)
I	Few constraints to crop production	15.0
II	High temp., low SOC, high shrink/swell	90.3
III	Seasonal wetness, short growing season due to low temp., minor root restriction	4.5
IV	Impeded drainage, crusting, compaction, high AEC	8.3
V	Excessive leaching, calcareous/gypsiferous soils, Al toxicity, seasonal moisture stress	103.7
VI	Saline/alkaline soils, low moisture and nutrient status, acid sulphate soils, high nutrient fixation	6.0
VII	Shallow soils	25.8
VIII	Extended periods of low temperatures, steeplands	4.7
IX	Extended periods of moisture stress	38.9

PROCESSES OF WATER LOSS FROM AGRICULTURAL SOILS

Components of the water balance over a landscape or watershed are shown in Figure 1. Total amount of water received over a watershed can be classified into *green water* and *blue water* (Röckstrom and Falkenmark, 2000). *Green water* is transpiration water, i.e., water that is directly involved in photosynthesis and the net primary productivity. *Green water* can be productively used in transpiration (T) or unproductively used in soil evaporation (E) (Röckstrom, 2001). The *blue water* comprises surface runoff (R) and deep drainage (D). In arid and semi-arid regions, with low vegetation cover and crusted/compacted soils, the R component can be high, especially in environments where the rainfall is concentrated over a short period. For example, India receives most of its rainfall in about 100 hours (Agarwal, 2000; Swaminathan, 2001) or no more than 25 nonconsecutive days (Biswas, 2001). Therefore, the main issue is how the enormous amount of rainfall received over a short period be converted from *blue water* to *green water*. Finding a technically feasible and cost-effective solution to this dilemma is a high priority (Röckstrom et al., 2002). The objective of a successful water management strategy is to

FIGURE 1. Processes of water loss from agricultural watersheds. The objective of water management is to maximize *green water* by minimizing E and recycling R and D.



minimize runoff (R) and soil evaporation (E), and to maximize soil water storage (θ). There is an inverse relationship between R and infiltration (I). In contrast, there is a direct relationship between I and θ, and I and D. In some situations, increase in D is necessary to recharge the ground water. The magnitude of R can be reduced by constructing a farm pond or a reservoir for storage of excess runoff and reuse it for supplementary irrigation.

Water balance studies, preferably done on small agricultural watersheds, are needed to assess the components outlined in Figure 1 so that land use, soil management, and farming systems can be chosen to maximize T and θ and to minimize R and E. Two examples of water balance studies conducted by ICRISAT in central India are shown in Tables 5 and 6. The data in Table 5 for an Alfisol, prone to crusting and hard-setting leading to low infiltration, show that 26% of the total annual rainfall was lost as surface runoff during the 5-year period from 1978 to 1982. Similar results for a watershed on a Vertisol, prone to cracking and with high swell/shrink

TABLE 5. Water balance components of an Alfisol (1978 to 1982) under traditional management in Central India (Laryea et al., 1991)

Components	Value (mm/yr^{-1})	% of Rainfall
Rainfall	907 ± 223	100
Runoff	236 ± 129	26
Evapotranspiration	373 ± 39	41
Deep percolation	298 ± 87	33

TABLE 6. Water balance components of a Vertisol (1976 to 1980) under traditional management in Central India (Laryea et al., 1991)

Components	Value (mm/yr^{-1})	% of Rainfall
Rainfall	757 ± 207	100
Runoff	214 ± 130	28
Evapotranspiration	292 ± 20	39
Deep percolation	71 ± 85	9
Soil evaporation	180 ± ?	24

properties leading to very low water infiltration, show that 28% of the rainfall received was lost as runoff over the 5-year period from 1976 to 1980. In both cases, construction of water reservoirs or farm ponds would be necessary to store the excess water during the rainy season for use as supplemental irrigation during the dry season.

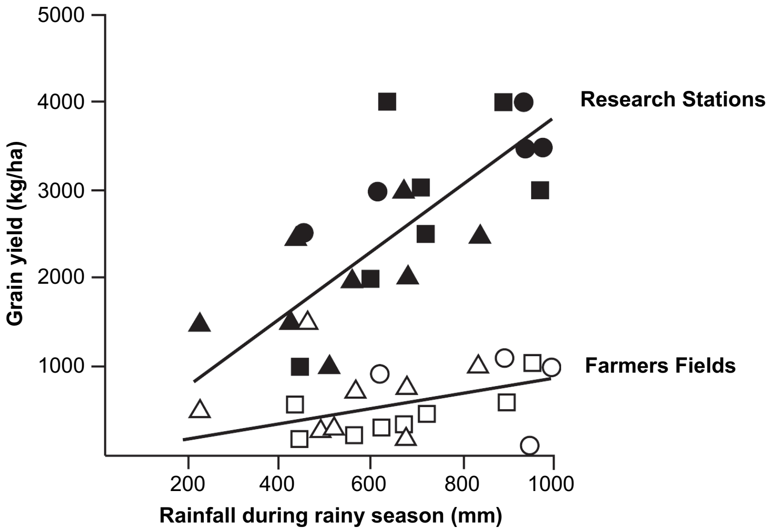
Soil evaporation is another form of water loss. High radiation, low humidity, and high air and soil temperatures cause severe losses of soil water by evaporation. The process of transient evaporation from soil occurs in three stages: (1) the constant rate stage of high evaporation, (2) the falling rate stage or the condition when the rate of evaporation decreases with decline in soil wetness, and (3) the stage of low evaporation when the soil is dry (Bond and Willis, 1969; 1970; Adams et al., 1976). The evaporation rate during the first stage is very high and depends on the evaporative demand of the atmosphere. The evaporation rate during the third stage is low and depends on soil properties. The duration of the first rate stage depends on the evaporativity or evaporation demand of the atmosphere, which can be controlled through altering the energy load reaching the soil surface. Using mulch during the first stage of high evaporation rate is very effective in reducing the evaporativity and in prolonging the duration of the time when soil remains wet. Using mulch during the third stage of low evaporation and when soil wetness is low has no effect on water conservation, although it can favorably change the soil temperature regime by reducing the maximum soil temperature.

The rainfed agriculture in India, as well as in other arid and semi-arid regions, is characterized by erratic and high-intensity rainfall concentrated during 2 to 4 months, along with recurrent droughts and dry spells. Extensive research has been done to determine the relation between crop water use and biomass production, cumulative crop water requirements in support of scheduling irrigation, and effects of drought stress on crop growth at different growth stages. However, practical data on strategies for managing crop water deficit in rainfed agriculture are lacking. Strategic information of practical importance to managing drought stress includes the partitioning of rainfall into *blue water* and *green water*, and the latter into nonproductive (soil evaporation) and productive (transpiration) *green water*, and judiciously using *blue water* to enhance transpiration or the *green water* flow (FAO, 1997). It is important to know the amount of *green water* in the root zone that crops can absorb, and how the *green water* can be increased.

NEED FOR SOIL WATER CONSERVATION

Low crop yields in rainfed agriculture are attributable to recurring drought stress, confounded by supra-optimal soil temperatures and high evaporative demand. Bouman and Tuong (2001) observed that water productivity is low, even in irrigated rice, due to severe losses of water. Water productivity of irrigated rice is 0.2 to 0.4 g grains per kg of water use in India, compared with 0.3 to 1.1 g per kg of water use in the Philippines. There are 4.3 Mha of upland rice in India (Kar et al., 2004), and the grain yield is <1 Mg ha^{-1} primarily due to prolonged periods of moisture deficit. In most rainfed crops, less than 10% of the total rainfall received is actually utilized by crops (Röckstrom, 1995); the remainder is lost either as runoff or soil evaporation. Thus, water conservation in the root zone is important for alleviating the drought stress, increasing yield, and improving productivity or WUE. The data in Figure 2 show a linear increase in crop yield corrdates with on increase in rainfall received during the growing season. However, the lower rate of increase in crop yield under on-farm conditions than in research plots indicates low WUE and high losses with traditional farming practices, and hence the large scope for potential

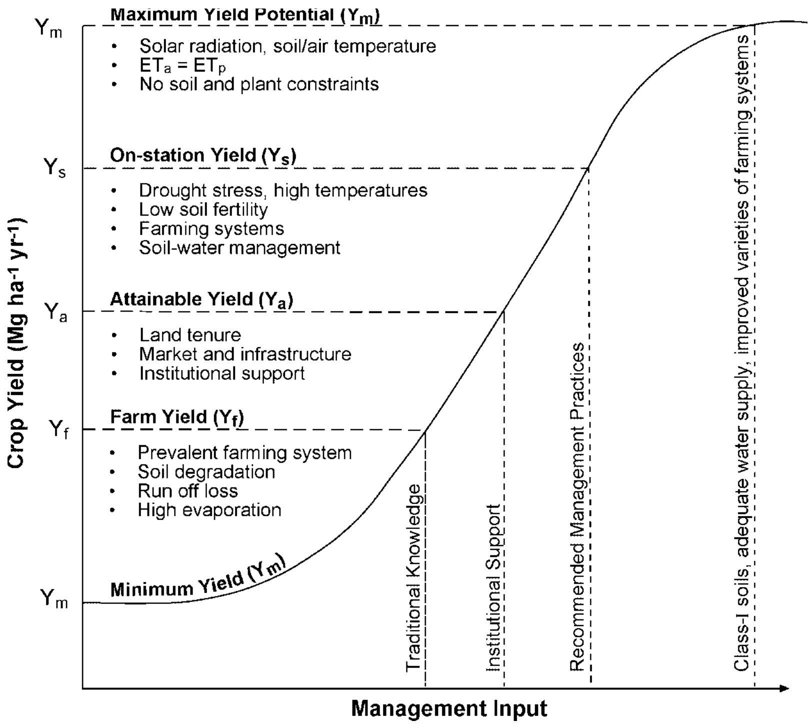
FIGURE 2. Relationship between rainfall during the rainy season and yield of maize (●), sorghum (■) and millet (▲) grown at research stations (closed symbols) and farmers' field (open symbols) at 15 dryland locations in India (adapted from Sivakumar et al., 1984).



improvements in managing soil water. The data in Table 6 also show a large yield gap between the national average yield and the national demonstration plot yield or the national demonstration highest yield. The ratio of national demonstration highest yield: national average yield ranged between 3 and 4 for chickpea, groundnut, maize, mustard, and soybean crops. However, the ratio was 11 to 12 for pearl millet and sorghum (Table 7). The data in Figure 3 and Table 7 are indicative of the potential of doubling (or even quadrupling) crop yields in rainfed agriculture through on-farm management of water resources involving runoff management and soil-water conservation in the root zone, along with adoption of improved cultivars and integrated nutrient management (INM) technologies.

The maximum or potential crop yield in an agro-ecosystem is determined by climate, soil properties, and genetic factors (assuming no losses due to pests). Climatic and soil factors that reduce the achievable yield from its maximum potential are (i) climatic constraints, (ii) soil limitations, and (iii) plant limitations (Röckstrom and Falkenmark, 2000). Climatic constraints include inadequate and erratic rainfall, spatial and temporal

FIGURE 3. A conceptual relationship between crop yield and management input. The yield gap between on-farm yield and on-station yield can be narrowed through adoption of recommended management practices.



variability in rainfall, high temperatures leading to severe losses by evaporation causing water deficit, and drought or dry spells. Within limits, climatic constraints can be managed by maximizing the productive *green water*. Soil limitations include textural and structural properties, which limit water retention in the root zone. Shallow effective rooting depth, nutrient deficiency, low soil organic carbon (SOC) pool, unfavorable pH, and high salt concentration also limit crop water uptake. Plant limitations include shallow root system, susceptibility to diseases, and poor canopy characteristics. The maximum crop yield is obtained when actual evapotranspiration (ET_a) equals potential evapotranspiration (ET_p) throughout the growing season, and there are no soil and plant limitations. The ratio ET_a: ET_p is called the "crop stress factor" (Boonyatharokul and Walker, 1979; Röckstrom and Falkenmark, 2000). The strategy is to

TABLE 7. Actual and potentially attainable yields in India (Prasad and Reddy, 1991)

Crop	National Average Yield (1)	National Demonstration Plot Yield (2)	National Demonstration Highest Yield (3)	Ratio of NDHY: NAY
	Mg ha^{-1}			
Chickpea	0.68	1.55	2.66	3.9
Groundnut	0.84	1.98	3.23	3.8
Maize	1.28	2.92	4.50	3.5
Mustard	0.70	0.89	1.93	2.8
Pearl Millet	0.40	1.70	4.50	11.3
Sorghum	0.57	3.27	7.05	12.3
Soybean	0.60	1.45	2.50	4.2

minimize the crop stress factor or maximize ET_a and alleviate soil and plant limitations. It is a tall order, given the fragile soils, harsh climate, resource-poor small land holders, and weak institutions.

The data in Table 7 and Figure 2 show that the gap between farmer yield and on-station yield is large. There exists a vast scope for enhancing agricultural production in India, because of the large gap between the climate/ecological potential, especially with regards to the yields of rice and wheat in the Indo-Gangetic Plains (Pathak et al., 2003). The large yield gap is attributed to numerous constraints, which must be systematically assessed and alleviated through adoption of a judicious land use, and of recommended management practices (RMPs). Extensive yield decline in the rice-wheat system (Ladha et al., 2003) may be due to decline in soil quality (Lal et al., 2004). Analysis of site-specific limitations affecting the yield gap is important to alleviate these constraints. The schematics in Figure 3 show a conceptual relationship between crop yield and managerial input. The yield gap between the ecologically maximum yield (Y_m) and on-station (Y_s) is attributed to soil limitations, and differences in ET_a and ET_p caused by rainfall deficit and temporal variability or an uneven distribution. The difference between attainable yield (Y_a) and on-station yield (Y_s) is caused by socio-economic and institutional factors such as land tenure, access to market, availability of input, and institutional support such as extension services, etc. The gap between on farm yield (Y_f) and Y_a is caused by the use of traditional rather than improved farming systems, serious problems of soil degradation (e.g., salinity, low soil fertility, crusting, compaction, erosion), and loss of water by runoff and high evaporation. The minimum yield (Y_m) is obtained under the most adverse conditions, and may often be zero. The objective is to increase the national average yield to the Y_s level by identification and management of soil, hydrological, and plant-related constraints.

PRINCIPLES OF SOIL WATER MANAGEMENT

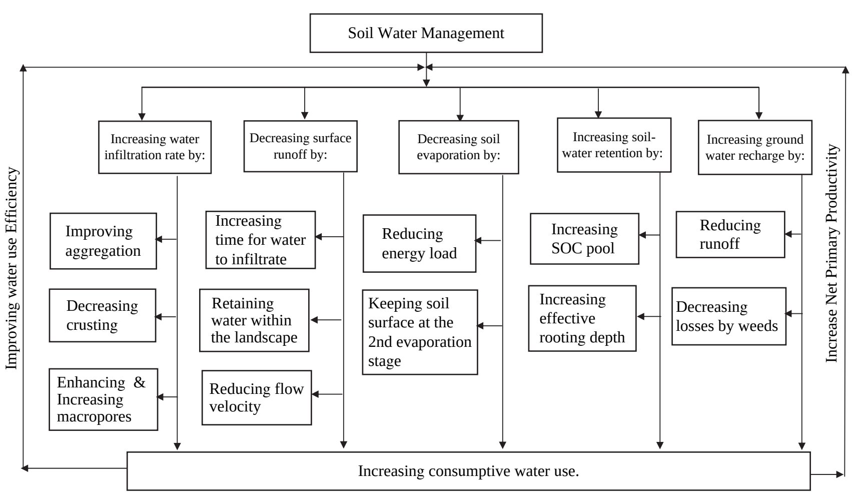
Careful analyses of the components of the hydrologic regime outlined in Figure 2 indicate basic principles of soil-water management as described in Figure 4. Two basic strategies of managing the soil water and enhancing the *green water* flow involves manipulating the components of water balance equation:

$$P = R + I + D + \Delta\theta + \int Edt + \int Tdt$$

Where P is total precipitation, R is surface runoff, I is infiltration, D is deep drainage, Δθ is change in soil water storage, E is soil evaporation, T is transpiration or green water, and t is time.

a. Enhancing quantity of *green water* by increasing I and D and decreasing R, and
b. Increasing flow of *green water* by increasing θ and decreasing E.

FIGURE 4. Basic principles of soil water management.



Increasing Water Infiltration

Soil water infiltration capacity can be enhanced by improving the amount and stability of structural aggregates, increasing soil aggregation, enhancing total and macro-porosity, and decreasing crusting and compaction. Soil application of biosolids, gypsum, manure, compost and other soil amendments that enhance aggregation and create biopores (through activity of earthworms and termites) improves water infiltration capacity. Infiltration rate of a crusted and compacted soil can also be increased by deep tillage (Nitant and Singh, 1995; Patil and Sheelavantar, 2006). In northwest India, Bhushan and Sharma (2005) reported that application of lantana residues as mulch increased both infiltration rate and hydraulic conductivity.

Decreasing Runoff

Increasing time for water to infiltrate the soil is a useful option for soils prone to high runoff losses caused by surface sealing. Several engineering devices can be installed to reduce the velocity of surface runoff. Important among these are contour ridges, tied ridges, the broad bed and furrow system, and other land-forming or configuration techniques (Smith et al., 1992; Selvaraju et al., 1999). Vegetative hedges (e.g., Veitver grass hedges) established on the contour can be effective in reducing runoff and conserving water (Jagannathan et al., 2000). Water storage in farm ponds and subsequent use for supplemental irrigation can increase crop yields. Kar and colleagues. (2006) reported that 380 mm of runoff water stored in farm pond can be used for 2 or 3 supplemental irrigations. Consequently, grain yield of crops increased by 87% to 96%. Average yield of upland crops was 1845 kg ha^{-1} for maize, 785 kg ha^{-1} for groundnut, 905 kg ha^{-1} for sunflower, 1420 kg ha^{-1} for wheat and 8050 kg ha^{-1} for potato (tubers). Harvesting and recycling runoff is an important strategy to mitigate drought and increase yield.

Reducing Soil Evaporation

In-situ water conservation, important to enhancing crop yields in dry-land farming (Patel, 2004; Muthamilselvan et al., 2006), involves reducing losses by soil evaporation. Decreasing energy load on the soil through use of crop residue mulch is an effective measure to reduce losses by soil evaporation especially when soil wetness is at the first or upper second stage of evaporation. Jalota and coworkers. (2001)

reported that straw mulching increased water storage in the root zone under low rainfall conditions and in coarse-texture soils. Mulching has little effect on decreasing evaporation losses and increasing water storage when soil wetness is low or at the third evaporation stage.

WATER HARVESTING AND RUNOFF FARMING

Rain water harvesting (RWH) is the method of inducing, collecting, storing, and conserving local surface runoff or *blue water* for agricultural production (Motsi et al., 2004). Water harvesting is especially useful for irrigating arid lands in regions with low (200 to 500 mm yr^{-1}) and erratic or unreliable rainfall. The practice of water harvesting and recycling for irrigation of cropland is also called "runoff farming." The latter involves growing crops on harvested and stored water by diverting runoff from a sloping land to a more productive farmland in the valley (Frasier, 2003; Storey, 2002). Small scale protective irrigation or runoff farming has been successful in India (Pangara and Pangara, 1992; Verma and Tiwari, 1995; Pangara and Lokur, 1996; Agarwal and Narrain, 1997; Gurjar et al., 2005). There are two approaches to water harvesting: interception ditches and water absorption barriers. The latter can be swales, ridge-furrow system, raised beds, or micro-basins. Raised beds and ditches have been cultural traditions of many ancient civilizations, and have traditionally been called by different names such as Chinampa (Mayan), Cajetes (Aztec), Waru-Waru (Incas), and Zai system (Africa). Large increases in crop yields have been reported from India by supplemental irrigation from water harvesting techniques (Willey et al., 1983; El-Swaify et al., 1983), and attainable crop yields are 2 to 3 times higher than the actual yields (Alexandratos, 1995; Le Houreau, 1996). Vittal and colleagues. (1996) reported that the water table in open wells was raised by 50 cm over 5 years by construction of percolation tanks, land-forming, and check dams in Andhra Pradesh, central India. Runoff losses were reduced by 26% and ground cover increased by 38% because of increase in cropping intensity (Vittal et al., 1996).

SOIL SURFACE MANAGEMENT AND CROPPING SYSTEMS

In addition to harvesting *blue water*, it is important to increase availability of *green water* through soil and crop management. The goal of soil management is to increase soil water retention, to reduce soil evaporation, and to increase root system development. There are several technological options for enhancing and managing soil water storage in the root zone. The most important among these are briefly described below.

Deep Tillage

If soils are compacted, such as are those with low SOC concentration and predominantly low activity clays, plowing deep and incorporating biosolids can improve surface detention capacity, increase infiltration rate, enhance plant-available water capacity, and increase crop yield under rainfed or dry-farming conditions. The data in Table 8 show that plowing deep increased yields of most crops by 20% to 60%, and of chickpea by 230%. Plowing deep also alleviates mechanical impedance of root growth in compacted sub-soil. Once the compacted soil is loosened by deep plowing, use of crop residue mulch in conjunction with no-till farming can conserve water and help to sustain high yields.

No-till

In contrast to deep tillage, some studies have also indicated the potential for reducing runoff and conserving water in the root zone by adopting conservation tillage, minimum tillage, or no-till farming (Rao et al., 1998). Rathore and associates (1998) conducted a 3-year study to assess the impact of no-till, minimum tillage, and conventional tillage (with and without straw mulch) on soil moisture conservation and yield of chickpea and mustard under rainfed conditions. Minimum tillage with or without straw mulch enhanced moisture storage on a deep clayey Vertisol and increased grain yield. In contrast, mustard growth and yields were better under no-till than

TABLE 8. Increase in yields of rainfed crops in India by deep plowing

Crop	State	Yield Increase (%)	Reference
Chickpea	A.P.	231	Laryea et al. (1991)
Maize	A.P.	29	Laryea et al. (1991)
Maize	Himachal	12	Acharya and Sharma (1994)
Pearl Millet	Tamil Nadu	33	Selva Raju et al. (1999)
Pigeonpea	M.P.	21–27	Nitant and Singh (1991)
Sorghum	A.P.	28	Laryea et al. (1991)
Sorghum	Karkatka	34–57	Patil and Sheelavantar (2006)
Sorghum (Tied ridges)	Tamil Nadu	34	Selva Raju et al. (1999)

under other tillage methods. In the western Himalayan region, Bhattacharya and colleagues (2006) assessed the impact of several tillage methods on yields for different crop rotations. The data in Table 9 show that saturated hydraulic conductivity and soil moisture retention constants were higher for no-till than for minimum tillage and conventional tillage methods. No-till systems improved hydrologic properties, even though soil bulk density was higher than under other tillage systems. Because of the contrasting response to tillage methods, it is appropriate to develop a soil guide to tillage methods (Lal, 1985). Developing appropriate agronomic methods for direct seeding of rice (rather than transplanting) may be needed to facilitate adoption of no-till farming in the rice-wheat system (Lal et al., 2004).

Mulch Farming

Use of crop residue mulch is beneficial to reducing losses caused by soil evaporation (Prihar et al., 1979; Singh and Singh, 1995; Jalota et al., 2001). Results of several experiments (collated in Table 10) show significant yield improvements among chickpea, maize, mustard, sorghum, and pearl millet crops from mulching. However, crop residues are removed for alternative/ competing uses (e.g., fodder, fuel), and are not available for mulching. Thus, there is a strong need to develop cropping systems that ensure availability of crop residues and other biosolids for mulching of rainfed crops. An important benefit of mulch farming is soil carbon sequestration with attendant improvement in soil quality and long-term productivity (Lal, 2004).

Synthetic Mulch

Plastic and paper mulches for soil water conservation and weed control are not widely used in India. Yet, the benefits on crop growth may be

TABLE 9. Tillage impacts on hydraulic conductivity of a soil in Uttaranchal, India (Adapted from Bhattacharya et al., 2006)

Soil depth (mm)	Conventional tillage	Minimum tillage	No-till	LSD (0.05)
	mm day^{-1}			
0–75	344	370	393	7.6
75–150	315	364	372	2.4
150–225	308	313	331	9.3
225–300	300	306	331	19.9

TABLE 10. Increase in crop yields by mulching of rainfed crops indifferent regions of India

Crop	State	% Increase by Mulching	Reference
Maize	A.P.	14–48	Cogle et al. (1997)
	Punjab	9–44	Prihar et al. (1979)
	Punjab	25–29	Ghuman and Sur (2001)
	Himachal	16–22	Acharya and Sharma (1994)
	Himachal	8–150	Sharma and Acharya (2000)
Sorghum	Central India	67–77	Randhawa and Venkateswarlu (1980)
	Andhra Pradesh	27–48	Cogle et al. (1997)

worth the cost (Kumar and Premi, 2003). This is an important research priority, and use of synthetic mulches needs to be assessed for food crops and high-value cash crops (Figure 5).

Cropping Systems

Choice of appropriate cropping systems, with high WUE and the ability to recycle nutrients, can improve and sustain agronomic productivity. Some agroforestry systems can be highly productive under conditions of low moisture availability (Ong et al., 2002). In the western Himalayan

FIGURE 5. Soil moisture conservation and weed control in cassava by using clear plastic mulch.

valley region, Narain and colleagues. (1998) reported that adoption of some agroforestry systems on sloping lands reduced losses by runoff, and utilized soil-water to 3 m depth. Wani and coworkers (2003) reported that improved cropping systems increased carrying capacity of a watershed on a Vertisol in central India. The improved system consisted of integrated land management to conserve soil and water, water harvesting and storage and INM used in conjunction with legume-based rotations. The average grain yield from improved system over a 24-year period was 4.7 Mg ha^{-1} yr^{-1} or about 5 times the average yield of 1 Mg ha^{-1} yr^{-1} for the traditional system. There was also an increase in SOC pool to 1.2 m depth which was 46.8 Mg ha^{-1} in the improved system compared with 39.5 Mg ha^{-1} in the traditional system. Legume-based cropping systems enhance productivity by improving soil fertility. The carrying capacity of improved systems was 18 persons per ha^{-1}, compared with 4 persons per ha^{-1} for the traditional system.

Soil Fertility Management

There is a strong link between nutrient availability and water use. Water use efficiency can be strongly improved by increasing availability of essential nutrients. Adopting the INM strategy is important to enhancing the availability of *green water*. Nutrient deficit, caused by extractive farming practices, reduces plant growth and decreases productivity over unit uptake of water. Soil fertility improvement through INM involves recycling plant nutrients by application of biosolids (e.g., compost, manure, mulch, sludge), biological N fixation through mixed cropping or rotational cropping with legumes, and supplemental use of synthetic fertilizers.

SPECIFIC RESEARCH NEEDS

The literature review on soil-water management indicates that a lot of useful and applicable research information is available. However, additional research is needed to determine the maximum/potential yield (Y_m) for predominant soils and agro-ecoregions using the crops/farming systems most suited for the region. It is important that factors responsible for yield gap between Y_a and Y_f, and Y_s, and Y_a are identified and managed to narrow the gaps. The yield gap can be narrowed by promoting adoption of RMPs. In this regard, the importance of on-farm validation and adaptation of RMPs based on the available information cannot be over-emphasized. There is a strong need for conducting inter-disciplinary on-farm research with farmer participation on validation and adoption of RMPs on benchmark sites in predominant agro-ecoregions of India to narrow the gap between Y_f and Y_s. The multi-disciplinary research should involve soil scientists, agronomists, foresters, hydrologists, agro-climatologists, plant scientists, economists and rural sociologists.

RMP's for these on-farm studies must be carefully chosen and in accord with specific soil and ecoregional characteristics. These RMPs should be validated on watershed basis.

CONCLUSIONS

On-farm crop yield in rainfed agriculture is low (< 1 Mg ha^{-1} yr^{-1}), and there is a large gap between on-station yield and attainable yield and actual farm yield. The yield gap can be bridged by increasing the relative proportion of *green water* by either reducing or harvesting *blue water*. Water harvesting and recycling (runoff farming) techniques are needed to manage *blue water*, and to convert it effectively into the productive *green water*. On-farm yield under rainfed agriculture can be doubled and even quadrupled through judicious management of soil water. Recommended management practices include deep tillage, conservation tillage, no-till farming, innovative farming/cropping systems based on improved varieties, and soil fertility improvement involving integrated nutrient management. Multi-disciplinary research is needed for predominant agro-ecoregions and principal soil types to assess (i) maximum/potential, on-station and attainable crop yields, (ii) components of the hydrologic cycle in terms of *green water* and *blue water*, and (iii) farmer acceptance of recommended management practices to maximize the productive *green water*.

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