12 Efficient Management of Rainwater for Increased Crop Productivity and Groundwater Recharge in Asia

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Abstract

Rainwater is the main source of water for agriculture but its current use efficiency for crop production ranges between only 30 and 45%. Annually, 300–800 mm of seasonal rainfall are not used productively, as the rainfall becomes surface runoff or deep drainage. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)'s long experience, in partnership with national agricultural research systems, in integrated watershed management has clearly demonstrated that areas with good soils in the semi-arid tropics (SAT) in Asia can support double-cropping, while surplus rainwater could recharge the groundwater. In the integrated watershed approach, the emphasis is on *in situ* conservation of rainwater at farm level, with the excess water being taken out of the fields safely through community drainage channels and stored in suitable low-cost structures. The stored water is used as surface irrigation or for recharging groundwater. Following conservation of the rainwater, its efficient use is achieved through choosing appropriate crops, improved varieties, cropping systems and nutrient and pest-management options for increasing productivity and conserving natural resources. Long-term, on-station watershed experiments have demonstrated that Vertisols with a rainfall of 800 mm have the capacity to feed 18 persons ha^{-1} (4.7 t of food grains ha^{-1}) compared with their current productivity of 0.9 t ha^{-1} supporting four persons ha^{-1}. This increased productivity can be achieved if the productivity of rainwater is doubled (from 30% to 67%) and the soil loss is reduced by 75% compared with the loss under traditional methods of cultivation. By adopting such a holistic approach to the management of rainwater in partnership with the communities, crop productivity in the watersheds is substantially increased (up to 250%), groundwater levels improved and soil loss minimized. Results from such on-farm integrated watersheds are discussed. Conditions for success in the improved management of rainwater are: community participation, capacity building at local level through appropriate technical guidance and the use of new scientific tools to manage the watersheds efficiently. To sustain agricultural productivity in the SAT, this holistic approach of watershed management needs to be scaled up through appropriate policy and institutional support and its on-site and off-site impacts need to be studied.

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Introduction

Water is the primary constraint in the semi-arid tropics (SAT) and its scarcity confounds the sustainability of agriculture in the SAT. If not managed properly, water adversely affects crop productivity and causes land degradation through runoff and associated soil loss. The SAT cover parts of 55 developing countries; they are the home of over 1.4 billion people, of whom 550 million are below the poverty line. Seventy per cent of all the poor people live in rural areas, where the key occupation is agriculture. The SAT are characterized by high water demand, with a mean annual temperature greater than 18°C. Rainfall exceeds evapotranspiration for only 2–4.5 months in the dry SAT and for 4.5–7 months in the wet–dry SAT (Troll, 1965). The coefficient of variation of annual rainfall ranges between 20 and 30% in these dry regions.

The rising demand for water for non-agricultural uses is proportionally reducing the water availability for agriculture. Thus efficient management of rainwater through water harvesting and improved water-use technologies helps increase productivity, reduces poverty and maintains the natural-resources base in the SAT.

Watershed as a Unit for Efficient Management

The watershed is a logical unit for the efficient management of rainwater in the dry regions. Along with water, other natural resources, such as soil, vegetation and biota, can also be managed efficiently by adopting an integrated watershed-management approach.

Based on impressive successes, with on-station watersheds using new technologies for double-cropping on Vertisols, researchers expected that this approach could be 'transferred' to farmers' fields, thereby enhancing the productivity of rain-fed systems. The whole process evolved around the 'demonstration' of the technology package and of its possible benefits under farmers' conditions. The two basic assumptions were that:

- All Vertisols faced the same degree of waterlogging, which could be alleviated by the adoption of broad bed and furrow (BBF).
- Farmers would adopt the technology once its benefits were demonstrated to the farmers under their specific conditions.

The Tadannapally village, Medak district in Andhra Pradesh, India, served as a test area for on-farm watershed trials by scientists of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in collaboration with Andhra Pradesh Agricultural Department officials. The Vertisol technology package was demonstrated in the village watershed. It included land smoothing, drain construction, the introduction of the BBF system, use of a bullock-drawn Tropicultor, summer cultivations, dry seeding and the use of appropriate nutrient and pest-management options along with improved high-yielding crop varieties. Yields in the improved watershed were compared with those in the traditional farmers' system. The trials performed during 1981/82 confirmed that on-farm yields could be similar to those from operational research watersheds. Of the latter, the improved productivity system with a sorghum + pigeonpea intercrop produced higher grain yields (1.9 t ha^{-1}) and net returns of Rs 3838 ha^{-1} year^{-1} compared with those from the traditional farmers' fields, which recorded 0.55 t ha^{-1} of grain yield and net returns of Rs 1234 ha^{-1} year^{-1}. Similar on-farm evaluations were done at several locations in Maharashtra, Gujarat, Madhya Pradesh, Karnataka and Andhra Pradesh.

However, subsequent evaluation of these watersheds after 15 years revealed that, in most of them, the farmers went back to their normal practices and that only selected practices were continued. As part of the watershed evaluation exercise, hundreds of farmers were interviewed and a multidisciplinary team of scientists analysed the process, farmers' interviews and possible reasons for the low adoption of the technology package.

Lessons Learned

Many lessons were learned from these studies, which need to be carefully applied in order to sustain the existing agricultural production systems in the SAT. Joshi *et al.* (1999) list the following:

- Components of Vertisol watershed technology, such as placement of seeds and fertilizers, improved varieties, use of fertilizers and summer cultivation, were already known and widely adopted by the farmers. However, their adoption increased after demonstration on the farmers' fields.
- The technology was found to be biased towards large farmers.

The whole technology package was not adopted by the farmers, but different components were. Several constraints affected the adoption of technology and higher adoption rates were observed in assured high-rainfall Vertisol areas.

ICRISAT's scientists have articulated the following additional lessons learned from years of working with watershed technologies (Wani *et al.*, 2001):

- Efficient technical options are needed to manage natural resources for sustaining systems.
- Mere on-farm demonstration of technologies by the scientists does not guarantee their adoption by the farmers.
- The contractual mode of farmers' participation adopted during Vertisol technology evaluation did not achieve the expected results. There is a need to have a higher degree of farmers' participation through a consultative to cooperative mode, from the planning stage up to the evaluation stage.
- Appropriate technology applications to address region-specific constraints need to be identified and simple broad recommendations do not help, e.g. Vertisols and BBF.
- Developmental projects lacked technical support so technical guidance is essential. No single organization can provide answers to all the problems in a watershed; thus, a consortium of organizations is needed for technical guidance.
- The process of partnership selection for each watershed has to be undertaken carefully and a generalized formula-based selection does not guarantee success.
- Technical change is intimately bound up with the broader institutional context of the watershed and the role of institutions and different players varies from location to location.
- Individual farmers should first realize tangible economic profits from the watersheds; it is only then that they come forward to participate in community-based activities in the watershed.
- A holistic-systems approach through the convergence of different activities is needed and it should improve farmers' livelihoods and not merely conserve soil and water in the watershed.
- Technological packages as such are not adopted and farmers adopted specific components that they found beneficial.
- There is no beginning or end to watershed inventions, and capacity building is critical for all the stakeholders. It is a continuous learning process.
- Women and youth groups play an important role in decision-making in the families.

New Integrated Watershed-management Model for Efficient Management of Natural Resources

A new model for efficient management of natural resources in the SAT has emerged from the lessons learned from extensive watershed-based research. The important components of the new integrated watershed-management model are as follows:

- The farmers' participatory approach through the cooperation model and not through the contractual model.
- The use of new science tools for management and monitoring of watersheds.
- Linking of on-station and on-farm watersheds.

- A holistic system's approach to improve livelihoods of people and not merely conservation of soil and water.
- A consortium of institutions for technical guidance on the on-farm watersheds.
- A microwatershed within the watershed, where farmers conduct strategic research with technical guidance from the scientists. Minimize free supply of inputs for undertaking the evaluation of technologies.
- Low-cost soil- and water-conservation measures and structures.
- The amalgamation of traditional knowledge and new knowledge for efficient management of natural resources.
- Emphasis on individual farmer-based conservation measures for increasing productivity of individual farms along with community-based soil- and water-conservation measures.
- Continuous monitoring and evaluation by the stakeholders.
- Empowerment of the community of individuals and strengthening of village institutions for managing natural watersheds.

Since 1999, using the new integrated water-management model, we have initiated new on-farm benchmark watersheds in India, Thailand and Vietnam. Five on-farm and three on-station watersheds in different agroecological, socio-economic and technological situations have been selected and work is ongoing in India, Thailand and Vietnam. As a case study, one on-farm watershed, the Adarsha watershed at Kothapally, Ranga Reddy district, in Andhra Pradesh, India, is described here. In addition, as illustrations of specific components of the new model, examples from other benchmark watersheds are also presented.

Use of New Science Tools for Managing and Monitoring Watersheds

Water budgeting using simulation models

For prioritization and selection of target regions for watershed development, first-order water budgeting using a geographic information system (GIS)-linked water-balance model is employed. Such a simulation model, used with monthly rainfall and soil data, generates output that can be used effectively to prioritize the regions and strategies for improved management of rainwater (Fig. 12.1). Once the target region is selected, then, for selection of appropriate benchmark sites, second-order water-budgeting studies using simulation models are applied For selected sites in the SAT of India, the WATBAL model (Keig and McAlpine, 1974) and weekly rainfall data of the past 30 years allowed the analysis of various soil-water availability and runoff (water surplus) scenarios. This is shown in Fig. 12.2 for four sites. High-rainfall locations selected were Bhopal, Nagpur, Indore and Adilabad, with annual rainfall ranging from 1000 to 1200 mm. The soils have a high water-holding capacity (≈ 200 mm). For these locations, the mean water surplus ranged from 270 to 508 mm during the season. Water surplus in 70% of the years (at the 30th percentile) ranged from > 130 to > 270 mm across locations. In 50% of the years it was > 230 to > 475 mm, indicating a tremendous opportunity to harvest rainfall in surface ponds or to recharge the groundwater.

At the medium rainfall (> 700 mm) locations, such as Hyderabad, Solapur, Aurangabad and Bangalore, the mean water surplus ranged from 66 to 187 mm annually. The soils in this region are Alfisols, Vertic Inceptisols and Vertisols, ranging in water-holding capacity from 100 to 200 mm in the root zone. Considering the depth of the soils at Hyderabad and Solapur, the opportunity for water harvesting exists for 50% of the years or less. However, on low water-holding capacity soils, such as Alfisols, it will be possible to harvest water in at least 70% of the years. At Aurangabad and Bangalore, the opportunities for water harvesting are greater, as the soils are shallower and of lower water-holding capacity. This analysis of the water balance indicates the opportunities for water harvesting and improved water management in different regions of the SAT, India, which would raise crop production from the existing low levels. It also provides information for selecting appropriate technologies, such as water harvesting or *in situ* water-conservation methods, which would be cost-effective and

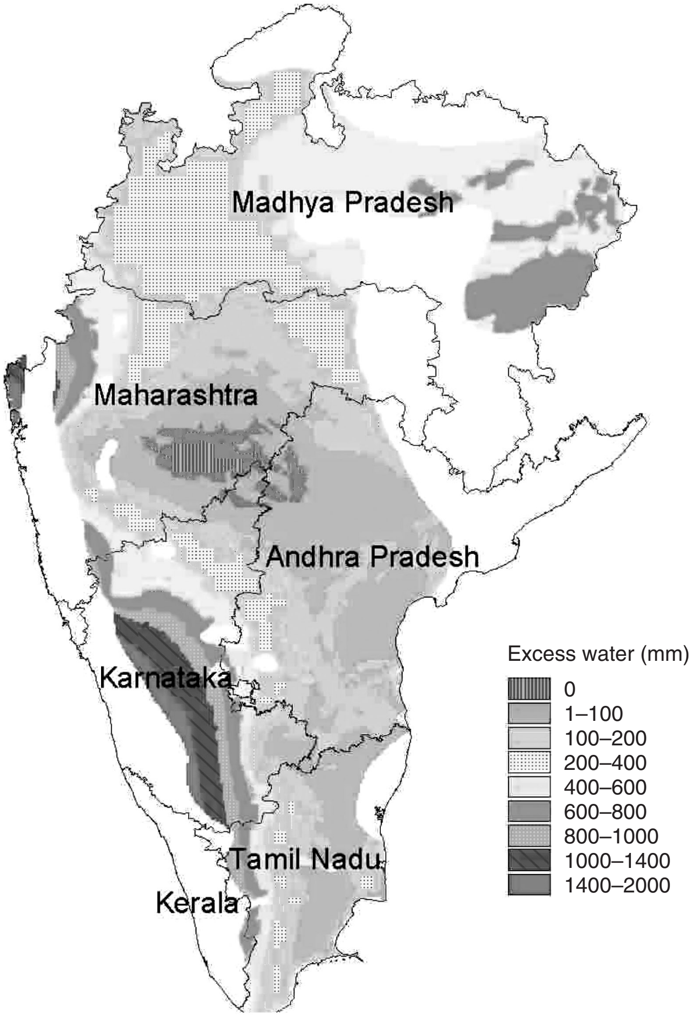

Fig. 12.1. Excess water available for harvesting as runoff in the states of the semi-arid tropics, India (June–October).

more impact-oriented about representative benchmark sites in the target ecoregion.

The CERES family of models has proved to be effective in simulating the water balance of soils with vertical drainage, which is often an unrealistic assumption. Runoff produced by such models is only from a point in space and no account is taken of water accumulation over space and time. In partnership with the Michigan State University (MSU), USA, through a US linkage grant to ICRISAT and with funding support from the Asian Development Bank, we have attempted to integrate the topographic features of the watershed in the hydrological models. The automation of terrain analysis and the use of digital elevation models (DEMs) have made it possible to quantify the topographic attributes of the landscape for hydrological models. These topographic models, commonly called digital terrain models (DTMs), partition the landscape into a series of interconnected elements, based on the topographic characteristics of the landscape, and are usually coupled to a mechanistic soil-water-balance model. The partitioning between

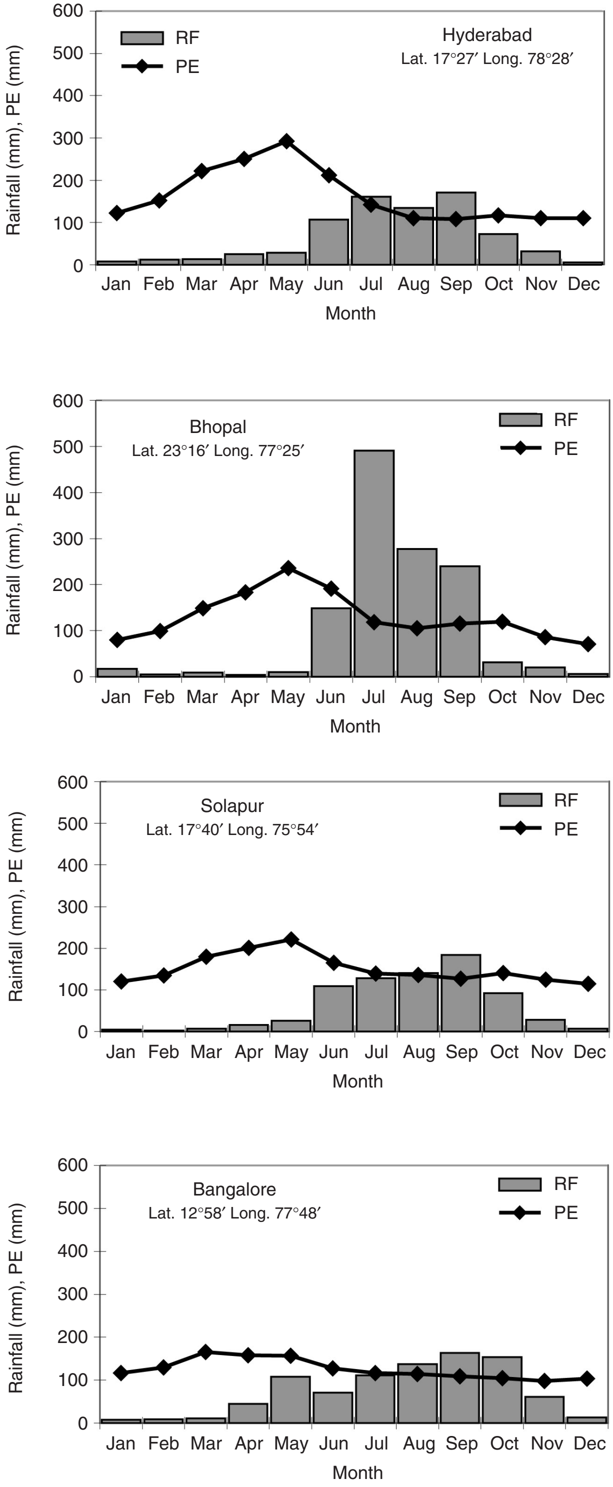

Fig. 12.2. Rainfall (RF) and pan-evaporation (PE) analysis for selected sites in the SAT, India.

vertical and lateral movement at a field-scale level helps to predict the complete soil-water balance and consequently the available water for the plants over space and time.

The data generated in the Black Watershed (BW) 7 on-station watershed at ICRISAT was used for validating the model developed at MSU. This partnership research led to the development of SALUS-TERRAE, a DTM for predicting the spatial and temporal variability of soil-water-balances. A regular grid DEM provided the elevation data for SALUS-TERRAE. We have successfully applied the SALUS-TERRAE, which has a functional spatial soil-water balance model, at a field scale to simulate the spatial soil-water-balance and identify how the terrain affects the water routing across the landscape. The model provided excellent results when compared with the field-measured soil-water content.

Feasibility studies for providing harvested water for crop production

For the Akola region, the simulated probabilities of getting 40, 60, 80 and 100 mm of water for supplemental irrigation from the runoff-harvesting structure are shown in Fig. 12.3. The probabilities of getting water for irrigation from the tank are high for most of the growing season. However, the high probability of getting 100 mm of irrigation water was limited to only 3 months, namely September, October and November. High runoff and low seepage loss are the main reasons for adequate availability of water in a harvesting structure. The 10 years of mean cumulative water-outflow data from the runoff-harvesting structure indicate that the structure could be enlarged, since approximately 2200 m^3 runoff water overflows from the structure every year. Overall, the analysis indicates a good prospect of runoff-water harvesting in the Akola region.

Crop simulation models for identifying the constraints and yield-gap analysis

We have validated the Decision Support System for Agricultural Technology (DSSAT) model for CROPGRO soybean and CROPGRO chickpea using the data sets generated from an on-station watershed at Patancheru. The validated models were used for estimating the potential soybean–chickpea system's yields in the target ecoregion, using the historical weather data for estimating the yield gaps. The soybean model and weather records of the past 22 years from Patancheru

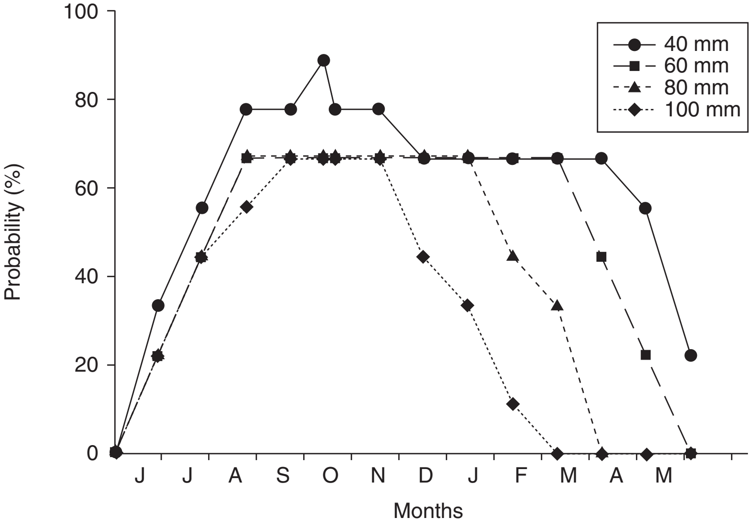

Fig. 12.3. Probabilities of obtaining 40, 60, 80 and 100 mm of water for irrigation from a tank at Akola (based on 10 years' simulated data).

were successfully used to evaluate the effect of soil depth on soybean yields. From the non-linear yield–soil-depth relationship obtained, it was observed that at Patancheru – even during a normal rainfall year – soybean cannot be grown in a soil with a depth of less than 37.5 cm. The analysis also revealed that, in 70% of the years, the soybean–chickpea system's yield at Patancheru could be 3.5 t ha^{-1} on medium-depth soil and 3.0 t ha^{-1} on shallow-depth soil (< 50 cm).

Crop simulation models, using a scenario analysis for yield-gap and constraint identification, simulate the crop yields in a given climate and soil environment. ICRISAT researchers have adopted DSSAT version 3.0, a soybean crop-growth model, to simulate the potential soybean yield in Vertisols at different benchmark locations (Tsuji *et al.*, 1994). The mean simulated yield was compared with the mean observed yield of the last 5 years to calculate the yield gap. The results (shown in Table 12.1) indicate that there is a considerable potential to bridge the yield gap between the actual and potential yield through the adoption of improved resource-management technologies. Such a scenario analysis helps the researchers to identify the high-potential areas where large yield gaps exist and considerable gains in productivity can be achieved.

Economic evaluation of tank irrigation systems

The economic evaluation of tank irrigation for high-rainfall Vertisol areas has been carried out using a simulation model (Pandey, 1986). The model consisted of several component modules for rainfall, runoff, soil moisture and yield response to irrigation and tank-water balance. Simulations were run for three different seepage rates, namely, 0, 10, 20 mm day^{-1}, for a test site on a Vertisol in central India (Madhya Pradesh). Results obtained from the simulation indicate that, as the seepage rate increases, the optimal tank size also increases, while the optimal size of the command area and other factors, such as runoff volume and availability of irrigable land, become constraints. It was found that tanks are quite attractive for the

Table 12.1. Simulated soybean yields and yield gap for selected locations in India.

Location	Mean sowing date	Mean harvest date	Simulated yields (t ha^{-1})		Mean observed yield[a] (t ha^{-1})	Yield gap (t ha^{-1})
			Mean	SD		
Primary zone						
Raisen	22 June	11 Oct.	3.05	1.28	–	–
Betul	19 June	8 Oct.	2.37	0.64	0.86	1.51
Guna	30 June	14 Oct.	1.69	1.96	0.84	0.85
Bhopal	16 June	8 Oct.	2.31	0.61	1.00	1.31
Indore	22 June	10 Oct.	2.30	0.98	1.12	1.18
Kota	3 July	16 Oct.	1.24	0.98	1.01	0.23
Wardha	17 June	6 Oct.	3.00	0.65	1.04	1.95
Secondary zone						
Jabalpur	23 June	11 Oct.	2.24	0.48	0.90	1.35
Amaravathi	18 June	8 Oct.	1.62	0.74	0.94	0.68
Belgaum	17 June	30 Sept.	1.99	0.66	0.57	1.42
Tertiary zone						
Hyderabad (shallow soil)	20 June	5 Oct.	2.70	0.69	–	–
Hyderabad (medium-deep soil)	20 June	5 Oct.	2.66	0.70	–	–

[a] Mean of reported yields of last 5 years.

SD, standard deviation.

soybean–wheat cropping pattern, the most common in the region, even at seepage rates as high as 20 mm day^{-1}. With the soybean + pigeonpea intercrop, the tank is profitable at seepage rates of less than 10 mm day^{-1}.

Linking On-station Strategic Research with On-farm Watersheds

The operational-scale watersheds at ICRISAT, used since 1976 and aimed at increasing productivity and improving soil quality through an integrated watershed approach, were a logical choice to study rainwater harvesting for increased productivity and groundwater recharge. The technology package developed by ICRISAT for enhancing productivity on Vertisols consists of summer cultivation, BBF for draining excess rainwater safely out of the field, dry planting, grassed waterways, use of an improved bullock-drawn Tropicultor for field operations, improved stress-tolerant crop varieties and appropriate nutrient and pest-management options. This package has shown promising results.

Improved vs. conventional systems – Vertisol watershed

In an improved system with all the options mentioned above, the average productivity was 4.7 t ha^{-1}, which indicates a carrying capacity of 18 persons ha^{-1} year^{-1}, whereas the traditional system with farmer-adopted practices yielded only about 0.9 t ha^{-1} and had a carrying capacity of only four persons ha^{-1} year^{-1} (Fig. 12.4). Along with this higher productivity, the improved system could also sequester more carbon (0.335 t ha^{-1} year^{-1}) and improve soil quality (Wani *et al.*, 2000). Most importantly, in the improved system, 67% of the rainfall was used by the crops, while 14% of the rainfall was lost as runoff and 19% as evaporation and deep percolation. In the traditional system, only 30% of the total rainfall was used by the crops, while 25% was lost as runoff and 45% as soil evaporation and deep percolation. The soil loss in the improved system was only 1.5 t ha^{-1}, compared with the traditional system, where the soil loss was 6.4 t ha^{-1}.

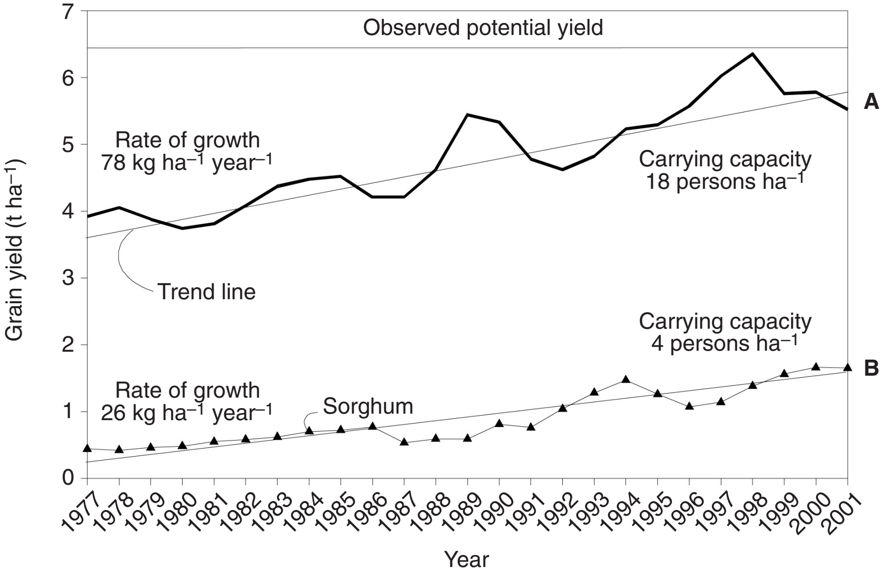

Fig. 12.4. Three-year moving average of grain yield under improved (A) and traditional (B) technologies on a Vertisol watershed at ICRISAT (1977–2001).

Increased productivity – Vertic Inceptisol watershed

At ICRISAT, Patancheru, crop productivity and resource use were studied for a soybean–chickpea sequential and soybean + pigeonpea intercrop systems on two land-forms (BBF and flat) and with two soil depths (shallow and medium-deep) at a watershed scale on a Vertic Inceptisol. The results show that, during 1995–2000, the improved BBF system recorded on average 0.1 t ha^{-1} more grain yield than the flat land-form. During 2000/01, when recorded rainfall was 958 mm (31% above normal rainfall), the BBF system yielded 500 kg more grains in the soybean–chickpea sequential system than in the flat land-form treatment. Similarly, an increased crop yield of 2.9 t ha^{-1} of soybean intercropped with pigeonpea on BBF was recorded compared with 2.63 t ha^{-1} in the flat land-form treatment. The total runoff was higher in the flat land system (23% of the seasonal rainfall) than on the improved system (15% of the seasonal rainfall). The BBF had more deep drainage than the flat land system, especially for the shallow soil. The runoff figure in the flat land system (190 mm), with a peak runoff rate of 0.096 m^3 s^{-1} ha^{-1}, compared unfavourably with the BBF system, which had a lower runoff (150 mm) and a lower peak runoff rate (0.086 m^3 s^{-1} ha^{-1}). Hence, the BBF system was useful in decreasing runoff and increasing rainfall infiltration. The soil loss in the flat land system was 2.2 t ha^{-1} versus 1.2 t ha^{-1} in the BBF system.

These studies clearly demonstrate the potential of Vertisols and Vertic Inceptisols with 800 mm of annual average rainfall at the watershed level. They also show that similar high yields could probably be achieved at the field scale if the same approach is followed.

Response of crops to supplemental irrigation

Once the rainwater has been harvested, it needs to be used efficiently to increase the system's productivity. The option to use the harvested rainwater for supplemental irrigation during a stress period was evaluated at ICRISAT and other research stations in India.

Benefits of supplemental irrigation in terms of increasing and stabilizing crop production have been impressive even in dependable rainfall areas of both Alfisols and Vertisols (El-Swaify *et al.*, 1985; Vijayalakshmi, 1987; Pathak and Laryea, 1991; Oswal, 1994; Singh *et al.*, 1998). As shown in Table 12.2, good yield responses to supplemental irrigation were obtained on Alfisols in both rainy and post-rainy seasons. The average irrigation water productivity (WP) (ratio of increase in yield to depth of irrigation water applied) varied with the crop, e.g. for sorghum it was 14.9 kg ha^{-1} mm^{-1} and for pearl millet it ranged from 8.8 to 10.2 kg ha^{-1} mm^{-1}. Tomatoes responded very well to supplemental water application, with an average WP of 186.3 kg ha^{-1} mm^{-1}. In the sorghum + pigeonpea intercrop, two irrigation turns of 40 mm each gave an additional gross return of Rs 3950 ha^{-1}. The largest additional gross return from the supplemental irrigation was obtained by growing tomato (Rs 13,870 ha^{-1}).

On Vertisols, the average additional gross returns due to supplemental irrigation were about Rs 830 ha^{-1} for safflower, Rs 2400 ha^{-1} for chickpea and Rs 3720 ha^{-1} for chilli. The average WP was largest for chickpea, with 5.6 kg ha^{-1} mm^{-1}, followed by chilli, with 5.3 kg ha^{-1} mm^{-1}, and safflower, with 2.1 kg ha^{-1} mm^{-1}.

Farmers' Participatory Approach: Selection of Watershed, Prioritization and Execution of Works

The adoption of integrated watershed management on farm is possible through community initiatives and strength of local participation. People's participation in planning, developing and executing the watershed activities is indispensable.

ICRISAT, Drought Prone Area Project (DPAP) officials, non-governmental organizations (NGOs) and farmers formed a consortium and visited three priority villages in the targeted Ranga Reddy district in Andhra Pradesh. The consortium partners jointly selected the Kothapally watershed as the participatory on-farm watershed, as the village did not have a single tank for community use.

Table 12.2. Grain-yield response (t ha^{-1}) of cropping systems to supplemental irrigation on an Alfisol watershed, ICRISAT Centre.

One irrigation turn of 40 mm	Increase due to irrigation	WAE[a] (kg ha^{-1} mm^{-1})	Two irrigation turns of 40 mm each	Increase due to irrigation	WAE[a] (kg ha^{-1} mm^{-1})	Combined WAE (kg ha^{-1} mm^{-1})
Intercropping system						
	Pearl millet			Pigeonpea		
2.353	0.403	10	1.197	0.423	5.3	6.8
	Sorghum			Pigeonpea		
3.155	0.595	14.9	1.22	0.535	6.7	9.4
Sequential cropping system						
	Pearl millet			Cowpea		
2.577	0.407	10.2	0.735	0.425	5.3	6.9
	Pearl millet			Tomato		
2.215	0.35	8.8	26.25	14.9	186.3	127.1

[a] Water application efficiency (WAE) = $\dfrac{\text{Increase in yield due to water application}}{\text{Depth of irrigation}}$.

The maximum area was cultivated with rainfed crops and the yields were low (1–1.5 t ha^{-1}). Moreover, during the initial visit and subsequent reconnaissance surveys, farmers showed a keen interest in participation in the watershed programme. The *Gram Sabha* (a general meeting of all the villagers) ratified the decision to select the watershed and agreed to take an active part in the watershed programmes. Subsequently, villagers' committees, self-help groups and user groups did all the planning and execution of the various watershed works.

Microwatershed Development as an Island for Testing Technology, Evaluation and Monitoring

Within a watershed of 470 ha, a microwatershed of 30 ha was delineated and developed, and subsequently the impact of watershed development on runoff, soil loss and nutrient losses was monitored. Both developed and undeveloped microwatersheds were fully instrumented with automatic runoff-recording and sediment-loss-gauging stations. In addition, rain gauges were fixed across the watershed to measure the rainfall variation in the watershed. In the microwatershed, farmers conducted simple trials to compare improved crop varieties, land-form treatments, balanced-nutrient schedules, integrated pest-management (IPM) and integrated nutrient-management (INM) options, etc. Farmers were given technical support but no inputs were provided free of cost for evaluating the technologies. The type of tests farmers conducted included comparing improved land-form treatments, such as BBF and contour planting, using an improved bullock-drawn Tropicultor versus the normal practice of sowing crops with the traditional wooden plough. Other trials involved fertilization and the various improved crop-management options mentioned above. Field experimentation by the farmers did not remain confined to the microwatershed, as a large number of farmers conducted trials throughout the watershed.

Increased productivities with improved management practices at Adarsha watershed, Kothapally

At Kothapally, farmers evaluated improved management practices, such as sowing on a

BBF land-form, flat sowing on contour, fertilizer application, nutrient-management treatment along with *Rhizobium* or *Azospirillum* sp. inoculations and using an improved bullock-drawn Tropicultor for sowing and intercultural operations. Farmers obtained a twofold increase in yield in 1999 (3.3 t ha^{-1}) and a threefold increase in 2000 (4.2 t ha^{-1}), as compared with the yields of sole maize (1.5 t ha^{-1}) in 1998 (Table 12.3). Intercropped maize with improved practice in pigeonpea gave a fourfold maize yield (2.7 t ha^{-1}) compared with yields on traditional farmers' fields of 0.7 t ha^{-1}. In the case of sole sorghum, the improved practices increased yields threefold within 1 year. In 1999/2000, farmers achieved the highest systems productivity, total income and profit from improved maize–pigeonpea and improved sorghum–pigeonpea intercropping systems (Table 12.4). Moreover, the cost–benefit ratio of the improved systems was more (3.5 times) than the traditional cotton-based systems (Wani, 2000). In 2000/01, several farmers evaluated BBF and flat land-form treatments for shallow and medium-depth black soils using different crop combinations. On average, farmers harvested 250 kg more pigeonpea and 50 kg more maize per hectare using BBF on medium-depth soils than with the flat land-form treatment. Furthermore, even with the flat land-form treatment, farmers harvested 3.6 t of maize and pigeonpea using the improved management options compared with 1.72 t of maize and pigeonpea grains using the normal cultivation practices (Table 12.5). Farmers with shallow soils and with other cropping systems reported similar benefits from the improved BBF land-form and

Table 12.3. Average crop yields from on-farm evaluation of improved technologies in Adarsha watershed, Kothapally, 1998, 1999 and 2000.

Crop	1998 baseline	Yield (t ha^{-1}) 1999	2000
Sole maize	1.50	3.25	3.75
Intercropped maize	–	2.70	2.79
(farmers' practice)		0.70	1.60
Intercropped pigeonpea	0.19	0.64	0.94
(farmers' practice)		0.20	0.18
Sole sorghum	1.07	3.05	3.17
Intercropped sorghum	–	1.77	1.94

Table 12.4. Total productivity, cost of cultivation for different crops at Kothapally watershed during crop season 1999/2000.

Cropping systems	Total productivity (t ha^{-1})	Cost of cultivation (Rs ha^{-1})	Total income (Rs ha^{-1})	Profit (Rs ha^{-1})	Cost: benefit ratio
Maize/pigeonpea (improved)	3.3	5,900	20,500	14,600	1: 3
Sorghum/pigeonpea (improved)	1.57	6,000	15,100	9,100	1: 2
Cotton (traditional)	0.9	13,250	20,000	6,750	1: 1
Sorghum/pigeonpea (traditional)	0.9	4,900	10,700	5,800	1: 2
Green gram (traditional)	0.6	4,700	9,000	4,300	1: 2

Table 12.5. Productivities in different on-farm trails at Kothapally during 2000/01.

System	Soils	Land-form	Yield (t ha^{-1}) (1)	Yield (t ha^{-1}) (2)	Total systems productivity (1 + 2)
Maize/PP	Shallow	BBF	1.75	0.38	2.13
Maize/PP	Shallow	Flat	1.68	0.29	1.97
Maize/PP	Medium	BBF	2.83	1.07	3.90
Maize/PP	Medium	Flat	2.78	0.82	3.60
Sorghum	Medium	BBF	3.00	–	3.00
Maize/PP	(Local farmers' practice)		1.49	0.22	1.71
Sorghum/PP	(Local farmers' practice)		0.47	0.11	0.59
Sorghum	(Local farmers' practice)		1.01	–	1.01

1. Main crop (maize or sorghum).
2. Component crop (pigeonpea (PP)).

other management improvements. In this area, rainfall during 1999 was 559 mm, which was 30% below normal rainfall, and in 2000 the rainfall was 958 mm, 31% above normal. In spite of this variation in rainfall (Tables 12.3 –12.5), productivity of the crops continued to show a marked increase during these years.

Nutrient-budgeting approach – boron and sulphur amendments

At the Lalatora watershed, a detailed characterization of soils revealed that they are deficient in boron (B) and sulphur (S), while both these nutrients are critical for optimizing productivity of soybean-based systems. Farmers were made aware of the results and some farmers came forward to evaluate the response of B and S application in their fields along with the improved management options. Farmers applied 10 kg of borax (1 kg B) and 200 kg ha^{-1} of gypsum (30 kg S). The treatments studied were: best-bet (control) treatment, B application, S application and B + S application. In 2000, all the farmers reported significant differences in soybean plant growth with B, S and B + S treatments over the control treatment. Soybean yields increased by 19–25% percent over the best-bet control treatment (Table 12.6). In 2000, soybean yields in the control were 1.52 t ha^{-1} – that is, 18% more than the 1999 best-bet treatment yields of 1.28 t ha^{-1}. The results indicate that B and S amendments not only increase soybean yields over the best-bet treatment but also benefited the subsequent wheat crop without further application of B and S. This residual benefit of B and S amendments for the subsequent wheat crop were to the tune of 31 to 40.6% over the best-bet treatment. The system's productivity when soybean was followed by wheat increased by 27–34% over the best-bet treatment. The farmers were so much impressed with their experimentation that for the 2001 season they indented B and S for their use well in advance on cost basis through the NGO the Bharatiya Agro

Table 12.6. Soybean yields with boron, sulphur and boron + sulphur treatments.

Treatment	Grain yield (t ha^{-1}) Soybean	Grain yield (t ha^{-1}) Wheat	Soybean–wheat system
Boron	1.87 (23.2)[a]	3.74 (40.6)	5.61 (34.2)
Sulphur	1.81 (19.1)	3.5 (31.9)	5.31 (27.0)
Boron + sulphur	1.91 (25.6)	3.57 (34.2)	5.48 (31.1)
Control (best-bet treatment)	1.52	2.66	4.18

[a] Values in parentheses are percentage increases over control (best-bet treatment).

Industries Foundation (BAIF). Noting the results of these farmers' experiments in the Lalatora subwatershed, farmers in other subwatersheds of the Milli watershed also volunteered to conduct these experiments in their fields during the 2001 rainy season.

Consortium Approach for Technical Guidance

A consortium of various institutes and organizations, as shown in Fig. 12.5, provides technical support for each on-farm benchmark watershed.

Empowering the Stakeholders through Training

Farmers were exposed to new methods and technologies for managing natural resources through training and field visits to on-station and on-farm watersheds. Farmers and landless families were trained and encouraged to undertake income-generating activities in the watershed, which can be of help in sustaining its productivity. The training sessions for farmers included training in on-farm operating implements and IPM and INM options. Other key agents of change, such as watershed committee members and agricultural and extension officials, were also trained at ICRISAT on different aspects of integrated watershed management. Special efforts were made to educate and increase the awareness of women farmers regarding new management options, as women play a key role in the adoption of a new technology. Many women were trained in vermicomposting technology at Kothapally. Educated youth were trained in skilled activities such as nuclear polyhedrosis virus (NPV) production and vermicomposting, which provided them with a source of income.

Continuous Monitoring and Evaluation

To know the impact of watershed management, continuous monitoring and impact assessment were done in respect of various determinants. Where relevant, examples of initial results of the monitoring exercise are inserted between square brackets.

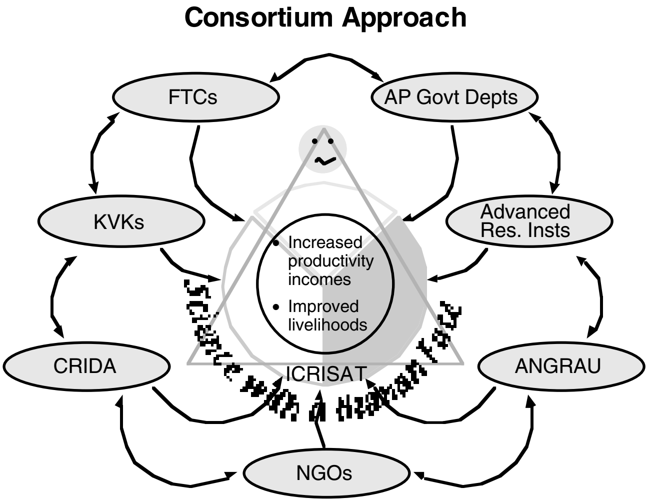

Fig. 12.5. A consortium of various institutions and organisations that provide technical support to each on-farm benchmark watershed. FTCs, farmers' training centres; KVKs, Krishi Vigyan Kendras (farm science centres); CRIDA, Central Research Institute for Dryland Agriculture; NGOs, non-governmental organizations; ANGRAU, Acharya NG Ranga Agricultural University; AP, Andhra Pradesh.

- Weather: an automatic weather station is installed to continuously monitor the weather parameters.
- Groundwater: open wells in the watershed are georeferenced and regular monitoring of water levels is carried out. [Hydrological investigations of the existing wells in the watershed indicated a rise in groundwater levels (5–6 m) at Kothapally (Fig. 12.6).]
- Runoff, soil and nutrient loss: these are monitored using automatic water-level recorders and sediment samplers. [Runoff as a ratio of the seasonal rainfall was observed to be 7% in the undeveloped watershed and 0.6% in a developed watershed, where soil- and water-conservation measures, such as gully plugging and bunding, had been adopted.]
- Pest monitoring: pheromone traps were installed to monitor *Helicoverpa* populations and, where appropriate, pest-control measures through IPM options have been started.
- Crop productivity: yields are recorded for each crop every year. [Data were analysed in terms of net income and the results from 1999–2001 were described in the previous section.]
- Nutrient budgeting: soil-nutrient levels are monitored and studies are being conducted to determine the optimum doses of fertilizers to maintain the soil-nutrient balance. Biological nitrogen fixation in farmers' fields is quantified using the N difference method and ^{15}N isotope-dilution method.
- Satellite monitoring: changes in cropping intensity, greenery, water bodies and groundwater levels are monitored. [GIS maps indicating soil types, soil depths and crops grown during the rainy and post-rainy season have been prepared.]

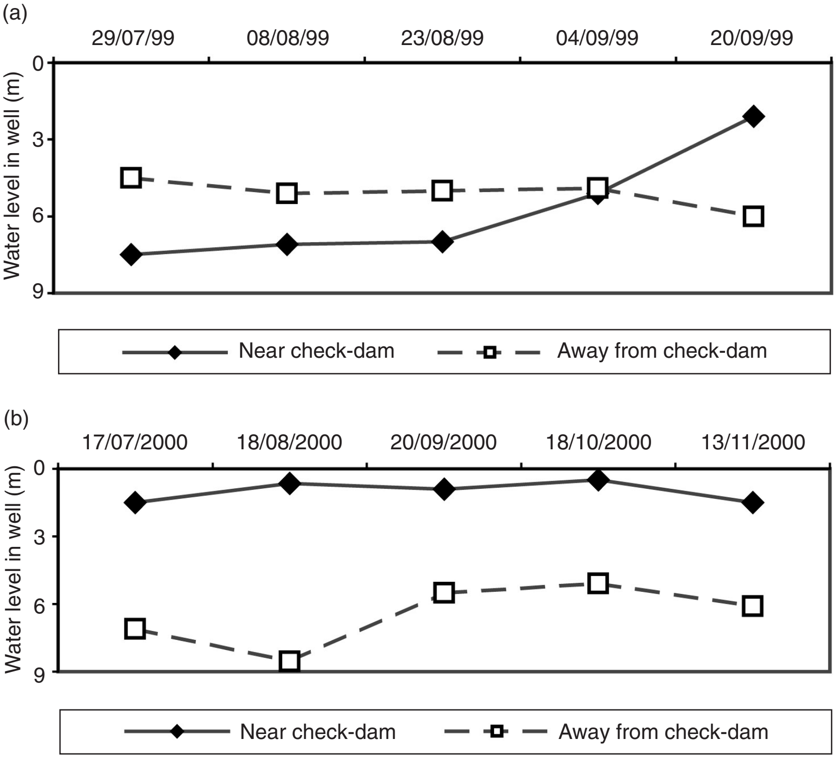

Fig. 12.6. (a) Groundwater levels before construction of check-dam in Adarsha watershed at Kothapally during 1999; (b) Effect of check-dam on groundwater levels in Adarsha watershed at Kothapally during 2000.

Emerging Issues

Despite the adoption of the integrated watershed approach for water harvesting and efficient use of natural resources, certain important issues need to be addressed as they have a bearing on sustainable production in the SAT. One of them is the need to better understand the motives behind collective action and the role of gender in the adoption of new technologies in the watershed framework. These issues are equally as important as the technical and economic factors. In the past, little attention was given in on-farm watershed work to farmers' participation, community action, group formation and empowerment of farmers. This has undoubtedly contributed to very low adoption rates, as well as to the unsustainability of many watershed technologies.

Some emerging issues are as follows:

- An integrated watershed is a continuous process, and the issue is how to plan and finance the activities involved. What training and incentives are most successful?
- How to institutionalize technical guidance for the watersheds.
- How to harmonize existing village institutions with committees especially set up for managing the watershed, and with other self-help groups. How to increase the efficiency of all these efforts through collective action.
- How to develop and enforce policies for rainwater harvesting. Who is entitled to its use? Who is responsible for the maintenance of rainwater-harvesting structures, wells and groundwater recharge? How to sustain the management of the watershed, i.e. how to make the community aware of the continuous efforts required for sustaining the productivity of the watershed, and how to ensure the ongoing participation of all stakeholders.
- How to include in the monitoring and assessment studies an evaluation of all on-site and off-site impacts of the watershed-development programmes.
- How to plan an exit strategy from watersheds and ensure sustainability through development of institutional and policy options.

Conclusion

An in-depth analysis of the possible scenarios of SAT farming systems reveals that the key elements of efficient management of rainwater are community participation, capacity building at local level through technical guidance by a consortium of organizations and use of high-science tools to manage the watershed efficiently. To sustain the productivity in the SAT, a holistic approach of integrated watershed management needs to be scaled up through appropriate policy and institutional support and its on-site and off-site impacts need to be studied.

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