# Integrated Watershed Management for Sustaining Crop Productivity and Reducing Soil Erosion in Asia

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## INTRODUCTION

Of all the human-induced land degradation problems, the permanent loss of soil productivity due to erosion is the worst on a global scale, and Asia has probably suffered more from human-induced soil erosion than any other continent. Loss of soil productivity that reduced the human carrying capacity of the land was highlighted more than a thousand years ago. Eckholms (1977) documented environmental degradation and cited erosion in deteriorating mountain areas as a major contributor to a chronic reduction in food production in developing countries.

Soil erosion is a natural process but can be accelerated by human activity and can threaten food production potential. Loss of the fine, nutrient-rich topsoil through erosion results in lower productivity, and silting of water bodies and streams (Black, 1968). It also induces erosion-triggered release of soil C from particulate organic material, which is a cause of global warming.

In the semi-arid tropics (SAT), which include those tropical regions typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils, appropriate management of water also contributes to sustainable agriculture. Improper management of water can cause land degradation through runoff and associated soil loss and reduce crop productivity significantly.

This paper presents some results of the watershed research conducted by the International Crop Research Institute for the Semiarid Tropics (ICRISAT) both on station and on farm. The on-farm research is conducted in India, Thailand, and Vietnam through the project "Improving Management of Natural Resources for Sustainable Rainfed Agriculture" (RETA 5812) funded by the Asian Development Bank (ADB)

## THE SEMI-ARID TROPICS (SAT)

As already mentioned, the SAT are typified by unpredictable weather, erratic rainfall, and nutrient-poor soils. Rainfall exceeds potential evapotranspiration in only 2.5 to six months in a year. The SAT are spread over 48 developing countries covering a geographical area of approximately 17.6 million km$^2$. This region is densely populated with about 850 million people, one-sixth of the world's population. About 380 million of these people are absolutely poor, unable to meet minimum standards of health and nutrition.

Despite many technological advances that have contributed significantly in advancing irrigated agriculture, rainfed agriculture continues to be beset with problems of unsustained production. Optimized management of natural resources is still a major factor in semi-arid agricultural productivity. Rainfall occurs in torrential downpours and most of it is lost as runoff causing *inter alia*, severe soil loss; therefore rainwater harvesting and management are important. Temporal variability in the amount and distribution of rainfall creates a highly uncertain agricultural environment, which results in food insecurity for the poor farmers and discourages them from making any productive investment in agriculture.

Securing food and water and maintaining the ecological balance are major research and development challenges for agriculture in the years ahead. The unprecedented increase in population,

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large withdrawals of groundwater resources, land degradation, deforestation, establishment of industries, and the movement of capital to these high climatic risk areas have contributed to unsustainable production leading to recurrent economic losses.

## WATERSHED MANAGEMENT

Watershed management is defined as an integration of technologies within the natural boundaries of a drainage area for the optimum development of land, water, and plant resources to meet the basic needs of people sutainably. Watershed management solutions must address the problem of rural poverty, protect the natural resources, and rehabilitate degraded areas, particularly those that pose hazards to human life and welfare.

People's participation is critical for sustainable development and management of watersheds. Lack of involvement of people in the past in the management of watersheds has been a major hindrance in sustaining whatever conservation measures have been adopted. Over the years it has been realized that community participation must be a part of the watershed approach as a model for development.

Participatory watershed management is a process, which aims to create a self-supporting system essential for sustainability and development. The process begins with the management of soil and water, which eventually leads to the development of other resources. Human resource development and large-scale community participation is essential, since finally it is the people who have to manage their resources. Participation is the key to the success of any integrated watershed development programme.

## WATERSHED RESEARCH BY ICRISAT

The watershed-based research of ICRISAT was initiated with the following objectives: 1) to increase the productivity and sustainability of the medium and high water holding capacity soils in the intermediate rainfall region, and 2) to develop environmentally friendly resource management practices that will conserve soil and water resource.

Current model of watershed management research pursued at ICRISAT involves the concept of linking strategic SWNM research conducted on station with the on-farm development research conducted in partnership with farmers through national agricultural research systems (NARS) including nongovernmental organisations (NGOs). The main features are:

- Use of highly technical scientific tools such as GIS-linked simulation models and satellite data to develop and manage community watersheds.
- A multidisciplinary and multi-institutional consortium approach for technical backstopping of the development projects.
- The 'Islanding' approach: Microwatersheds are used as up-front demonstrations wherein strategic research and adaptive on-farm research in the area of integrated SWNM and integrated pest management is undertaken by the farmers with technical support from the consortium partners. This provides an effective mechanism to transfer technologies for managing natural resources to the farmers.
- Watershed planning, management of work, evaluation and monitoring done in partnership with the farmers and often the entire community is involved.
- Adoption of a holistic farming systems approach to sustain productivity and to improve land and environmental quality.
- Emphasis on human resource development for the NARS to undertake integrated watershed development and management in partnership with the stakeholders i.e., the farmers.

- Women empowerment through group training at the village and community level. Women are usually the critical group involved in decision making for the management of natural resources.
- Continuous monitoring and impact assessment as an integral feature, from the very beginning.

## On-station watershed research

The research work of ICRISAT has focused on the management of Vertisols and associated soil groups. Vertisols are deep heavy black soils with a clay, clay loam or silty clay loam texture. They have a high moisture retention capacity, are sticky when wet, and very hard and cracked when dry. They cannot be easily handled under either conditions. Traditionally, Vertisols are left fallow in the rainy season and cropped in the postrainy season on stored soil moisture. With this traditional fallowing, Vertisols are prone to severe erosion and not utilized to their full potential.

Vertic Inceptisols occur in association with Vertisols in a toposequence. They have similar physical and chemical properties as Vertisols. They are shallow and occur on slopes not exceeding 5%. They are prone to severe land degradation because of their location on a toposequence. Major constraints for sustaining the productivity of these soils are high runoff and associated soil erosion, depletion of soil nutrients and beneficial organisms leading to a decline in the productivity of the crops grown on them.

Two cropping systems, soybean-chickpea (sequential) and soybean+pigeon pea (intercropped) were studied on station at a watershed scale on a Vertic Inceptisol at ICRISAT centre. These systems were evaluated under varying soil depths (shallow and medium deep) and using two landforms (broad bed and furrow [BBF] and (flat). Surface runoff and deep drainage water were captured in tanks and excavated wells to provide irrigation to the crops. Water balance and soil erosion and productivity and sustainability were determined.

Using weather records from 1975 to 1996 for the ICRISAT centre, long-term simulations of water balance and the productivity of the soybean-chickpea rotation were performed for the four treatments using a crop-sequencing model DSSATv3. The hypothesis is that the productivity of the soybean and chickpea rotation system is affected by the depth of the soil profile, available soil moisture, landform, and weather variability. From the multi-year simulations, the cumulative probabilities or the cumulative density functions (CDF) for the crop yields and water balance components were calculated for various management strategies.

## On-farm watershed research

In order to scale up the benefits of integrated watershed management observed on an operational scale, on station, five on-farm benchmark watersheds were selected in central India, northern Vietnam, and northeastern Thailand. This was made possible through the project "Improving Management of Natural Resources for Sustainable Rainfed Agriculture" funded by the ADB. The sites have an annual rainfall ranging from 800–1,300mm and a medium to high water holding capacity (150 to 200 mm). Additional information on the sites is shown in Table 1.

All on-farm technology evaluation trials were conducted on benchmark watersheds in partnership with NARES, NGOs, and farmers. The on-farm watersheds vary from 30–10,000 ha with varying agroecological potential. The model described in the on station research is employed.

A detailed baseline survey was conducted in all the watersheds using participatory rural appraisal (PRA) techniques. Detailed baseline information about the land holdings, family structure, cropping systems adopted, fertilizers, pesticides, inputs used, outputs, and other socioeconomic details were collected. In each benchmark watershed, microwatersheds were delineated and developed for intensive data collection on various parameters and observations.

In each watershed, provisions were made to take excess water out of the fields safely and collect it in tanks, which can be used either for supplementary irrigation or for recharging the

groundwater. Two ponds in Vietnam, three in Lalatora, Bhopal, India, and three tanks in Kothapally, India were constructed. For data monitoring, various instruments such as automatic weather stations, automatic runoff recorders, and automatic sediment samplers were installed in all the microwatersheds.

Regular monitoring of various parameters was done to evaluate the impact of watersheds on crop productivity, environment, and socioeconomic changes. Runoff, soil losses, water and nutrient budgeting, groundwater levels, crop productivity, inputs used, and benefits to farmers were evaluated.

**Table 1.** Benchmark watersheds in India, Thailand, and Vietnam.

| Watershed location | Partner institutes | Agroclimatic characteristics | Cropping system |
|---|---|---|---|
| **India**<br>Lalatora, Vidisha | BAIF Development Research Foundation | Annual rainfall 1,200mm | Soybean-wheat |
| | Central Research Institute for Dryland Agriculture (CRIDA) Hyderabad. | Soils: Vertisols and Vertic Inceptisols | |
| Kothapally, Ranga Reddy | M.Venkatarangiah Foundation (MVF) (NGO); Drought Prone Area Programme (DPAP) (Government of AP), CRIDA, Hyderabad. | Annual rainfall 760mm<br>Soils : Vertic Inceptisols | Sorghum, maize, pigeon pea, and soybean-based system |
| Ringnodia, Indore | JNKVV (state agricultural university) CRIDA, Hyderabad. | Annual rainfall 1,050mm<br>Soils: Vertic Inceptisols | Soybean-chickpea<br>Soybean-pigeon pea |
| **Thailand**<br>Tad Fa,Khon Kaen | Department of Agriculture; Department of Land Development and Khon Kaen University | Annual rainfall 1,300mm<br>Soils : Sloping mixed heavy soils | Maize-legume |
| **Vietnam**<br>Thanh Ha, Hoa Binh | Vietnam Agricultural Science Institute | Annual rainfall 1,300mm<br>Soils : Deep Alfisols and sloping lands | Maize-based system |

## Other research

Soil, water, and nutrient management (SWNM) research is also conducted on soybean-based systems at IISS, Bhopal; ICRISAT, India, and JNKVV, India. Research on biological nitrogen fixation (BNF) research on soybean-based systems is done at the ICRISAT centre and IISS, Bhopal, India. In Khon Kaen, Thailand, it is done on a maize-legume system. Research on soil degradation is conducted at the ICRISAT centre and Khon-Kaen, Thailand while research on waterlogging is done at IISS, Bhopal, India.

# RESEARCH HIGHLIGHTS

## On-station research

At the ICRISAT centre, results showed the benefits gained from employing the improved system. Soil erosion was reduced, water balance was improved, and productivity increased. Simulation also showed the positive effects of the improved system.

## *Water balance and soil erosion*

The use of broad beds and furrows (BBF) reduced the average annual runoff to one-half and the soil loss to one-fourth as compared to that of the traditional system. In the improved system, 67% of the rainfall was used by the crops while 14 and 19% were lost as runoff and as evaporation and deep percolation, respectively. In the traditional system, a lower percentage (30%) of the total rainfall was used by the crops, and a higher amount was lost as runoff (25%) and as soil evaporation and deep percolation (45%). Soil loss in the improved system was also lower at 1.5 t $ha^{-1}$ compared to 6.4 t $ha^{-1}$ in the traditional system (Table 2).

**Table 2.** Annual water balance and soil loss (t $ha^{-1}$) for traditional and improved technologies in Vertisol watersheds, ICRISAT Center.

| | | Water-balance component | | | |
|---|---|---|---|---|---|
| **Farming system technology** | **Annual rainfall (mm)** | **Water used by crops (mm)** | **Water lost as surface runoff (mm)** | **Water lost as bare-soil evaporation and deep percolation (mm)** | **Soil loss (t $ha^{-1}$)** |
| *Improved system*[2] Double cropping on broad beds and furrows | 904 | 602 (67)[1] | 130 (14) | 172 (19) | 1.5 |
| *Traditional system*[3] Single crop in post-rainy season, and cultivation on flat | 904 | 271 (30) | 227 (25) | 406 (45) | 6.4 |

[1] Values in parentheses are amounts of water used or lost expressed as percentage of total rainfall.
[2] Improved system received 60: 20 kg N and P $ha^{-1}$
[3] Traditional system received 10 t of FYM $ha^{-1}$ once every two years; during the rainy season, the land was kept as cultivated fallow.

Total runoff was higher in the flatland system (23% of the seasonal rainfall) than in the improved system (15% of the seasonal rainfall) (Table 3). The runoff was greater in the flatland system (190 mm), with a peak runoff rate of 0.096 $m^3 s^{-1} ha^{-1}$ compared to the BBF system where runoff was comparatively lower (150 mm) and a lower peak runoff rate (0.086 $m^3 s^{-1} ha^{-1}$). The BBF system was useful in decreasing runoff and increasing rainfall infiltration. The soil loss in the flatland system was higher (2.2 t $ha^{-1}$) than in the BBF system (1.2 t $ha^{-1}$) (Singh *et al.*, 1999b).

**Table 3.** Measured peak runoff rate and soil loss in two landform treatments on a Vertic Inceptisol Watershed , ICRISAT Center, Patancheru.

| | **Rainfall (mm)** | **Runoff (mm)** | | **Peak runoff rate ($m^3 s^{-1} ha^{-1}$)** | | **Soil loss (t $ha^{-1}$)** | |
|---|---|---|---|---|---|---|---|
| | | BBF | Flat | BBF | Flat | BBF | Flat |
| | | | | **Medium depth** | | | |
| Mean | 805 | 150 | 188 | 0.082 | 0.096 | 1.5 | 2.2 |
| Range | 546–1,043 | 1–232 | 3–290 | 0.003–0.135 | 0.003–0.145 | — | — |
| | | | | **Shallow depth** | | | |
| Mean | 854 | 128 | 160 | 0.081 | 0.136 | 1.2 | 2.1 |
| Range | 546–1,043 | 2–251 | 2–283 | 0.003-0.130 | 0.004–0.235 | — | — |

*Source:* Singh *et al.* (1999b).

## Productivity and sustainability

The total productivity of the soybean-chickpea sequential system ranged from 2.5 to 2.8 t $ha^{-1}$ and from 2.0 to 2.2 t $ha^{-1}$ for the soybean+pigeon pea intercrop system. These yields are much higher than the current average yield of soybean in India of <1.0 t $ha^{-1}$.

Table 4 shows the nitrogen budget for the soybean-chickpea and the soybean + pigeonpea systems. The improved system (sowing on BBF + *Glyricidia* on bunds) resulted in a relatively balanced N budget (Table 4). *Glyricidia* cuttings provided 31 kg N $ha^{-1}$ $y^{-1}$ without adversely affecting crop yields of the nearby rows. Pigeon pea derived up to 89%, soybean up to 75%, and chickpea up to 42% of their N requirement through biological nitrogen fixation (BNF). In the conventional system (sowing on flat), relying only on the biological N source resulted in the depletion of soil N (about 50 kg $ha^{-1}$ $y^{-1}$) during first four years.

**Table 4.** Average nitrogen balance of soybean-based cropping systems on a Vertic Inceptisol watershed, 1995–98 seasons, ICRISAT Center.

| | Cropping systems | | | |
|---|---|---|---|---|
| | Soybean-chickpea | | Soybean/pigeon pea | |
| | BBF | Flat | BBF | Flat |
| Total 'N' uptake (kg $ha^{-1}$) | 197 | 198 | 220 | 214 |
| Total 'N' loss through runoff (kg $ha^{-1}$) | 13.4 | 17 | 14.1 | 17.4 |
| 'N' additions (kg $ha^{-1}$) (rainfall, fallen leaves, roots & BNF) | 165 | 167.7 | 200 | 182.7 |
| 'N' additions (kg $ha^{-1}$) (compost, *Gliricidia* loppings) | 45 | 0 | 44 | 0 |
| 'N' balance (kg $ha^{-1}$) | 0.0 | -47.3 | +10 | -48.7 |

## Simulation analysis

The long-term simulations show that runoff during the rainy season was greater for the medium deep soil than for the shallow soil (Table 5). For both soil depths, total runoff for the flat landform was greater than for the BBF landform. For most years, infiltration was increased in the BBF system in both the medium and shallow soil depths. This resulted in higher deep drainage as compared with the flat system. In terms of total productivity, Singh *et al.* (1999a), also using long-term simulation studies, showed that in 70% of the years, the soybean–chickpea crop rotation system exceeded 3,000 kg $ha^{-1}$ (range 3,000–4,150 kg $ha^{-1}$) for the shallow soil and 3,450 kg $ha^{-1}$ (range 3,450–4,700 kg $ha^{-1}$) for the medium deep soil.

**Table 5.** Simulated soil water balance of the soybean-chickpea sequential system on a Vertic Inceptisol watershed, 1995–1999 seasons, ICRISAT Center.

| | | Water balance components (% of rainfall) | | | | | |
|---|---|---|---|---|---|---|---|
| | Rainfall | Surface runoff | | Deep drainage | | Crop water use | |
| | (mm) | BBF | Flat | BBF | Flat | BBF | Flat |
| *Medium depth* | | | | | | | |
| Mean | 758 | 14 | 18 | 15 | 13 | 74 | 74 |
| Range | 532–973 | 0–24 | 1–30 | 0–25 | 0–21 | 57–100 | 58–100 |
| *Shallow depth* | | | | | | | |
| Mean | 758 | 13 | 17 | 25 | 21 | 70 | 71 |
| Range | 532–973 | 0–26 | 1–31 | 7–36 | 4–33 | 51–100 | 52–100 |

These results indicate that the BBF system is useful in decreasing runoff and increasing infiltration of rainfall in Vertic Inceptisols. Under this rainfall environment, there is a good opportunity for water harvesting in surface ponds and recovering the deep drainage water. The analysis also showed that crop yields could be substantially improved by increasing rainfall-use efficiency through appropriate land and water management practices in a watershed framework.

## On-farm watershed research

### *Baseline socioeconomic survey*

A case study in Thanh Ha Watershed in Vietnam showed that the total number of households in the watershed is 62. They have a small family size of four persons per family on average. Fifty eight percent of the population is 17–55 years.

The total land area is 163 ha and 56 ha are under cultivation; 83% of the cropped area is under maize with baseline productivity of 3.4 t $ha^{-1}$. Water melon and sugarcane are also cultivated to a small extent (6–8%) with yields of 18 and 60 t $ha^{-1}$, respectively.

### *Evaluation of improved management*

In Adarsha Watershed in Kothapally, India, results showed that improved management practices such as sowing on a BBF landform, flat sowing on the contour, and fertilizer application with an improved bullock-drawn tropicultor gave higher productivity and income for the farmers. In 1999, the yield of maize was doubled (3.3 t $ha^{-1}$) and tripled (4.2 t $ha^{-1}$) in 2000 compared to the yield in 1998 (1.5 t $ha^{-1}$). Maize intercropped with pigeon pea gave a yield of 2.7 t $ha^{-1}$ with improved practices compared to 0.7 t $ha^{-1}$ in the farmers' practice. Sole sorghum with improved practices tripled the yields within one year. The highest productivity and income came from improved maize-pigeon pea and sorghum-pigeon pea intercropping systems.

In Lalatora Watershed in Madhya Pradesh, India, improved management options were compared with the farmers' practice. In 1999, the best-bet options (improved variety, seed treatment with *Rhizobium* and phosphate solubilising bacterial culture along with 10 kg N, and 20 kg $P_2O_5$ as di-ammonium phosphate) yielded 34% more soybean than the farmers' practice. In 2000, boron application increased soybean yields by 35%, sulphur application by 34%, both boron and sulphur applied by 39%. Broad beds and furrows increased soybean yields by 18% compared to that following the farmers' practices.

### *Crop productivity in different toposequences*

In Thanh Ha Watershed, Vietnam, crops grown in the different parts of the toposequence yielded differently. Maize, groundnut, soybean, and mungbean showed higher yields in the middle and lower parts of the toposequence than those grown in the upper portion (Table 6). Soybean, which was newly introduced into the area, yielded 700–1,000 kg $ha^{-1}$. With improved management practices, mung bean yielded 34% higher in 1999.

In a similar study in Tad Fa Watershed, northeastern Thailand, maize grown on the lower portion of the toposequence gave the highest yield of 4.1 t $ha^{-1}$ compared to yields of 3.65 and 3.1 t $ha^{-1}$ on the middle and upper parts, respectively (Table 7). It is worth noting that the upper portion has a steep slope of >15%. The middle has a moderate slope of 5–15% and the lower has a slope of <5%. The steep slopes showed 25% loss in productivity due to land degradation. A simulation study showed that runoff accounted for 35–40% of the total rainfall and occurred mainly in the early season. (April) or during late rains (September–October).

**Table 6.** Varied crop yields on a toposequence, Thanh Ha Watershed, Vietnam.

| Crop | Year | Toposequence Top | Middle | Low |
|---|---|---|---|---|
| Maize | 1999 | 4.2 | 5.4 | 4.9 |
| | 2000 | 5.1 | 5.7 | 5.5 |
| Groundnut | 1999 | 1.7 | 2.1 | 2.4 |
| | 2000 | 2.7 | 2.8 | 3.1 |
| Soybean | 1999 | 0.75 | 1.1 | 1.03 |
| | 2000 | 1.4 | 2.3 | 2.8 |
| Mung bean | 1999 | — | 1.2 | 0.95 |
| | 2000 | 0.52 | 0.72 | 1.24 |

**Table 7.** Maize yields on a toposequence in Tad Fa Watershed in northeastern Thailand, 1999.

| Location | Grain yield (t ha$^{-1}$) | Simulated soil loss (t ha$^{-1}$) |
|---|---|---|
| Steep slope (>15%) | 3.1 | 300 |
| Moderate (5–15%) | 3.7 | 150 |
| Mild slope (<5%) | 4.1 | 20–50 |

Analysis of the soil profile samples to a depth of 1 m taken from all five watersheds also showed differences in microbial biomass and soil respiration values. Microbial biomass and soil respiration which can serve as direct measures of soil biological activity, varied significantly in the toposequence. Biomass C and respiration values of soil samples taken from the top 10 cm of the upper toposequence were similar to the values of the lower 10–20 cm samples from the middle part. This information will be useful in relating indicators of soil degradation with crop productivity losses.

## *Nitrogen balance*

Also in Thailand, the net nitrogen benefit for leguminous crops was positive (Table 8). Among the leguminous crops, sword bean gave the highest net N benefit of 51 kg ha$^{-1}$. Non-leguminous crops like maize tend to have negative net N benefit.

**Table 8.** Nitrogen content and amount of nitrogen fixed by selected legumes grown on Ban Koke Mon in northeastern Thailand, 1999–2000.

| Crop | N Content Fallen leaves | Seed N | Total N | N fixed (kg ha$^{-1}$) | Net N benefit (kg ha$^{-1}$) |
|---|---|---|---|---|---|
| Rice bean | 13.5 | 18 | 37 | 20 | 2 |
| Sunnhemp | 28.0 | 59 | 107 | 90 | 31 |
| Sword bean | 26.5 | 53 | 121 | 104 | 51 |
| Black gram | 11.9 | 19 | 44 | 27 | 8 |
| Maize | — | 13 | 17 | — | -13 |

## CONCLUSION

Integrated watershed management is a holistic approach that enables a win-win solution for sustaining productivity and reducing soil erosion that causes poverty in the rainfed areas of Asia. The current model for watershed research followed at ICRISAT links on-station to on-farm research and adopts the consortium approach with strong technical backstopping. Farmers' participation in on-farm research was successful in the area of SWNM research.

The current model of ICRISAT watershed research has a high potential for bringing favourable changes in the drylands of the semi-arid tropics. On-farm watersheds managed through community participation could sustain productivity of the drylands and preserve the quality of the land resources and environment. An holistic systems approach through integrated watershed management in participatory mode can result in sustainable management of land resources and achieving food security.

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## ACKNOWLEDGMENT

This report is based on the research conducted at benchmark sites in India, Thailand, and Vietnam for the project "Improving Management of Natural Resources for Sustainable Rainfed Agriculture" funded by the Asian Development Bank, Manila, Philippines, RETA 5812. The financial assistance provided by the ADB is gratefully acknowledged. At all the benchmark sites teams of scientists are involved in undertaking this research; their efforts are acknowledged.