New science tools for managing community watersheds for enhancing impact

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Abstract

One of the main reasons for low productivity in the rainfed SAT areas is lack of knowledge and use of new science tools; other reasons are the inherent low soil fertility, drought, severe degradation of natural resource base, poor infrastructure, low cash inputs, etc. At ICRISAT, lot of research on application of new science tools such as simulation modeling, geographical information systems (GIS), satellite imageries alone and in combination has showed that the efficiency and effectiveness of this research could be substantially improved. Use of GIS for characterizing the agro-ecosystems along with information on soils, crops, length of growing period and biotic and abiotic constraints enabled the researchers to identify the technology application domains effectively with less cost. The GIS along with simulation modeling particularly using the water balance model enabled to identify the quantities of excess water available during the season as well as to plan the watershed management activities. Further, using GIS and satellite imageries simultaneously at different times during the seasons enabled to identify about 2 million ha rainy season fallow lands in Madhya Pradesh, India. In the Indo-Gangetic Plains (IGP) in South Asia about 15 million ha land was found suitable for growing *rabi* (postrainy season) crops after growing rice in the system. This not only enabled the scientists to develop suitable crops and management options for crop intensification but also enhanced the sustainability of the systems as well as economic gains for the poor farmers. Use of simulation models enabled to assess the potential of different agro-ecoregions using important crops and identify the yield gaps existing between the farmers' fields and the achievable yields. Thus there is a need to scale-up the available technologies. Research is needed to minimize the gap between the achievable yield and potential yield. Simulation models also helped in identifying the constraints and suitable technology application domains without going through the process of conducting costly long-term experimentation with a number of management options. Most importantly using simulation modeling long-term impacts of different management options on C sequestration could be assessed which would have been not possible in all the cases using conventional long-term experimentation approach. This review study has shown that there are several new science tools to enhance the impact of agricultural research in rainfed areas of the SAT. Application of these new science tools has helped the researchers, policy makers as well as research managers to plan, execute and monitor the research and development programs in rainfed areas for reducing the poverty.

Introduction

One of the main reasons for low productivity of rainfed systems in the semi-arid tropics (SAT) is insufficient scientific inputs in terms of research and development; other reasons are the poor infrastructure, inherent low soil fertility, frequent occurrence of drought and severe degradation of natural resource base (Wani et al. 2003a). Generally, high science tools are applied in well endowed areas as the returns on the investments in terms of economic impact as well as adoption of the new technologies are quick and more. However, recent studies undertaken by the Asian Development Bank (ADB) has shown that not only the investments in rainfed areas are as productive as in the well endowed areas but also such investments are more effective in reducing the poverty in these hotspots of poverty. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in partnership with the national agricultural research systems (NARSs) has applied new science tools such as simulation modeling, remote sensing, geographical information systems (GIS) and satellite imageries for enhancing the productivity of rainfed systems in the SAT.

The spatial and temporal availability of data from the research has enhanced the availability of data immensely. If such vast quantity of data should be utilized effectively, we need ways and means to process it logically and interpret for the benefit of researchers as well as policy makers. GIS is a tool that relates information to places. It stores spatial data in a topological framework defining the relationships between map elements (points, lines, polygons and grid cells), facilitates convenient retrieval from the spatial database and supports analysis and modeling to be displayed as digital or hardcopy maps. By visualizing different types of data from different sources using digital maps, GIS cuts across communication boundaries and can become a medium for establishing a common language between otherwise contentious or disinterested groups. The ability of GIS to integrate and spatially analyze multiple layers of information is its core capability. Multi-criteria spatial queries help us visualize the spatial patterns and spatial relationships to understand the phenomenon under study. With the progress in computing capabilities and availability of hardware, more functionality is added to the GIS. Spatial modeling is the application of analytical procedures with GIS. Models are coupled in different ways with GIS to produce spatial model outputs. Either spatial data is used as input to specific models or vice versa to understand spatial phenomenon. GIS has perhaps the best use in the field of agriculture, as it is the most widely prevalent activity on the earth. GIS is used to understand spatial dimensions of varied problems in agriculture especially when environmental variables like climate, soils, water, etc play a major role in production, constraints and practices. Temporal data sets need to be analyzed, interpreted, and depicted suitably for better understanding. This need can be fulfilled by using GIS.

A series of agroclimatological studies on characterization and modeling of the agroclimatic environment in the SAT has provided a sound basis for the design and transfer of agricultural technologies throughout the SAT. In collaboration with the national research programs and meteorological services, we focused on a wide array of research areas such as agroclimatic resource characterization, temporal and spatial variability in rainfall, rainfall probabilities, probability analysis of soil water availability, water balance and length of growing season and empirical analysis of wet and dry spells and presented these using spatial tools along with crop production and natural resource data (Laryea et al. 1998, Huda et al. 2004).

Simulation modeling has been one of the major activities of ICRISAT's natural resource management (NRM) research. Since 1982, we have collaborated with national and international institutes in the development, testing and validation of water balance, crop simulation and soil management models for the SAT. For some crops such as groundnut (*Arachis hypogaea*), chickpea (*Cicer arietinum*), pigeonpea (*Cajanus cajan*) and pearl millet (*Pennisetum glaucum*), new knowledge was generated through field experimentation that led to the development and upgradation of these crop models to improve their reliability.

Research methodology

Distribution of soils in production systems in India. Production systems (PSs) based approach to agricultural research was found to be more relevant at ICRISAT during the 1990s and the SAT was divided into 29 production systems. A GIS database of PS maps consisting of soils, climate, crops and other socioeconomic variables is used. It was further proposed to refine these PSs using GIS to be able to compare with the national agro-ecological zones (AEZs) so that these PSs are useful for upscaling and downscaling of technologies (Johansen 1998).

Land use mapping for assessing fallows and cropping intensity. To delineate rainy season fallows in the state, data obtained from the Indian remote sensing satellite were analyzed. A deductive approach including delineation of agricultural land and forests from temporal satellite data was employed to identify (rainy season) fallow. Three sets of satellite data corresponding to three periods, namely mid-, late, and (postrainy) *season* were used. While mid-season satellite data provides the information on agricultural lands, which were lying unutilized along with those agricultural lands that have been supporting crops, the satellite data of *season*, on the other hand, exhibits the spatial distribution pattern of the land supporting crops. These lands include the areas, which were lying fallow during *season* in addition to the lands that were cultivated during *season*, and are now supporting crops. In contrast, the satellite data acquired during late season showed the agricultural lands that were lying fallow during *season* and the areas where crops were planted (Fig. 1). The state of Madhya Pradesh is covered by two WiFS (Wide Field Sensor) images. Owing to the presence of persistent cloud cover during *season*, the availability of cloud-free space borne multispectral data has been the major problem. However, very short repetitivity and tandem operation of the IRS-1C and IRS-1D satellites, along with the IRS-P3 satellite, enabled acquiring virtually cloud-free WiFS data of September from IRS-1D and IRS-P3 satellites. Furthermore, the situation remains more or less same even during post-monsoon period too. Consequently, cloud-free WiFS data were not available and out of two images covering the former state of Madhya Pradesh, one image for October was used. Satellite data acquired during peak growing period of crops, help identification of lands where crops have been taken.

The digital multispectral data from WiFS aboard IRS-1D/-P3 over the area acquired during the *season* of 1999–2000 and *season* of 2000–01 was utilized for deriving information on fallow lands. In addition, Survey of India topographic maps at 1:250,000 scale are also used (Fig. 2). The approach essentially involves preparation of the mosaic of WiFS digital data covering entire state, preliminary digital analysis, ground-truth collection, map finalization, and generation of area statistics.

Basically, a deductive approach was employed for delineation of fallow lands. Based on past experience, initially areas akin to fallow lands were identified after displaying the digital multispectral data onto color monitor of Silicon Graphics work station. Besides, topographic maps were used for exclusion of the areas with rock, outcrops, scrubs, hills, etc. Furthermore, other categories like forestland, cropland, wasteland, water and settlements were also broadly delineated. Doubtful areas were located in the topographic maps of 1:250,000 scale for further verification in the field.

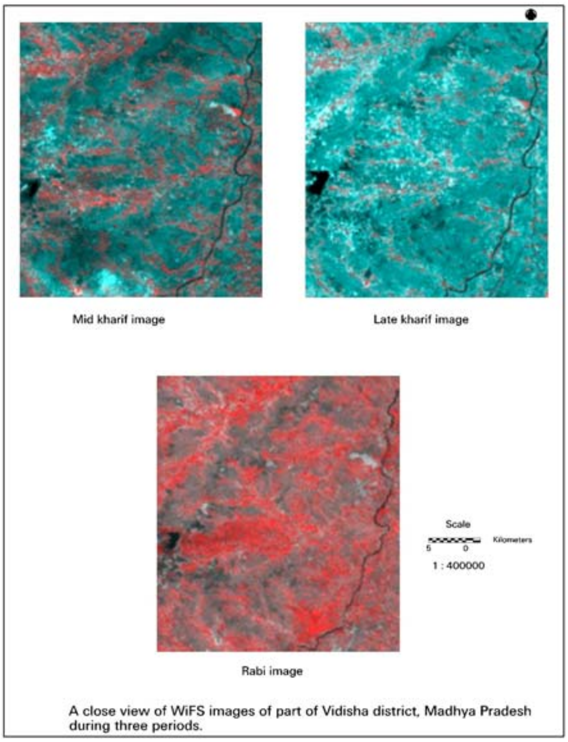


Figure 1. A close view of WiFS images of Vidisha district in Madhya Pradesh during mid-, late and postrainy season.

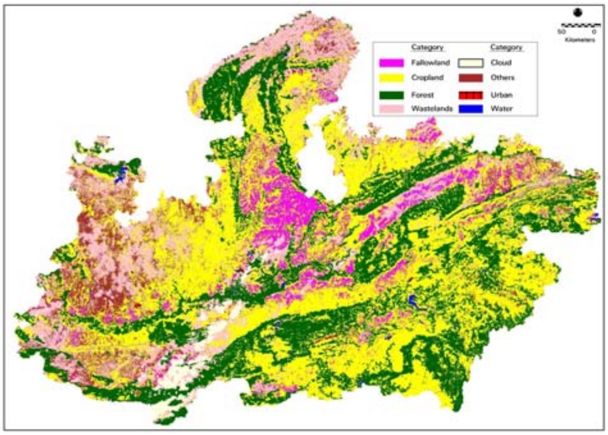


Figure 2. Spatial distribution of various land use and land cover categories in Madhya Pradesh.

The second generation of Indian remote sensing satellites (IRS-1C and IRS-1D) has better resolution and wide applicability for different applications. The WiFS sensor provides reflectance data in red and near infrared bands at 188 m spatial resolution and at 5 days revisit, covering a swath of about 812 km, and is useful in deriving regional level crop information. High frequency of the availability of the WiFS data due to the short revisit period also facilitates the monitoring of crops (Kasturirangan et al. 1996). WiFS data was found to be suitable for deriving regional information on the spatial distribution of rice (*Oryza sativa*) crops grown in the Godavari delta of East and West Godavari districts and pulse crops cultivated in the rice-fallow fields of the Krishna delta of Krishna and Guntur districts of Andhra Pradesh, India (Navalgund et al. 1996). In the present study, WiFS data of the 1999 and the 1999/2000 seasons was used to derive the regional level information on the spatial distribution of the rice and rice-fallow lands in the South Asian countries of Bangladesh, India, Nepal and Pakistan.

The reflectance spectra of plant canopies are a combination of the reflectance spectra of the plants and of the underlying soil (Guyot 1990). When a plant canopy grows, the soil contribution progressively decreases. Thus, during the active vegetative growth phase, the visible and middle infrared reflectance decreases and the near infrared reflectance increases. During senescence, the reverse phenomenon occurs. Maximum reflectance from the vegetation is sensed when the crop canopy fully covers the ground, which coincides mostly with the beginning of the reproductive phase. Hence, in this study, satellite data corresponding to this stage were selected to discriminate the rice crop in the season.

After the harvest of rice, the land will be either left fallow or cultivated with a suitable crop in the following season. The time gap between the harvest of rice and the cultivation of the crop depends upon the suitability of the prevailing weather, availability of water, etc. Satellite data of the period soon after the harvest of rice crop will depict large area under fallows though these lands are sown with crop because of poor manifestation on the image leading to an over-estimation of the fallow lands. In order to properly estimate the post-rice-fallows, the satellite data of period was selected based upon the prevailing cropping pattern of the region, and coinciding with the likely maximum vegetative stage of the dominant crop when the crop is manifested clearly and discernable on the satellite data (Subbarao et al. 2001).

GIS was used to create simple overlays of pedo-climatic variables along with the rice-fallow data generated from remote sensing satellite. The rice-fallow data were vectorized and used as a layer for overlay. ArcView software from ESRI (Environmental Systems Research Institute, California, USA) was used to make the overlays. The pedo-climatic variables were obtained from different sources [soils from the Digital Soil Map of the World (DSMW) (FAO 1996), climatic variables as gridded surfaces from International Water Management Institute (IWMI)]. A soil water balance model (WATBAL) (Keig and McAlpine 1974) was used to estimate the available soil water spatially (2.5 arc minutes 4.5 km approximately) and temporally (monthly) using the above pedo-climatic datasets. The program coded in Fortran is used in running the water balance model, which was developed by P Jones of CIAT, who patterned it after the Basic-Plus example by Reddy (1979). The program was modified to suit the available data. The input data for the WATBAL model are the precipitation and potential evapotranspiration (PET) as gridded interpolated surfaces from point data. The interpolated climatic surfaces are available at monthly temporal resolution. The maximum soil water-holding capacity (SWHC) is extracted from the Digital Soil Map of the World and its derived soil properties (FAO 1996). The SWHC is the upper bound of the moisture storage capacity class with highest percent value under the mapping unit. These raster surfaces, which are a matrix of gridded cell values, were converted to ASCII format for the purpose of faster processing and used as inputs to the model. The model estimates the available soil water at each precipitation during the month minus the soil water loss as actual evapotranspiration (AET) during the month. The AET during the month is calculated as the ratio of AET/PET multiplied by PET. The ratio of AET/PET was taken as equal to 1.0 for soil moisture percentages from 100% down to X% and decreases linearly to 0 thereafter, where X is calculated from a square root function, 3+3.868*(SQRT) (SWHC)), that fits the three values of X supplied by Reddy (1979) – 30, 50 and 70 for SWHC of 50, 150 and 300 mm, respectively. The outputs in the ASCII format are again converted into raster surfaces using ArcInfo GIS. This averaging process was intended only to give an overall impression at a national level of spatial and temporal variations in soil water availability parameters. It would not necessarily be sufficiently rigorous to accurately simulate soil water status at a given point in space and time.

Analysis of constraints and potential of the soils of the Indo-Gangetic Plains of Punjab using GIS. Soil map prepared using the Indian remote sensing satellite (IRS-LISS II) data for the state of Punjab was digitized using Arc/Info GIS. The 27 soil, site and chemical properties of the soils were keyed into Dbase table. This external attribute table was used to join the soil map to make thematic maps of the different soil properties. Soil properties like salinity, calcareousness, particle size, etc that are useful for constraint analysis were mapped to understand the spatial distribution of these attributes and the extent of each soil unit calculated from the maps.

Simulation modeling has been one of the major activities of ICRISAT’s NRM research. We have collaborated with national and international institutes in the development, testing and validation of water balance, crop simulation and soil management models for the SAT. For some crops such as groundnut, chickpea, pigeonpea and pearl millet, new knowledge was generated through field experimentation that led to the development and upgradation of these crop models to improve their reliability. NARS scientists were trained in the management of databases and model applications in their environments. Some recent examples of simulation modeling are the Decision Support Systems for Agro-technology Transfer (DSSAT), Agricultural Production Systems Simulator (APSIM), the Productivity, Erosion, Runoff Functions to Evaluate Conservation Technologies (PERFECT) and Crop Estimation through Resource Environment Synthesis (CERES) model. Some of the important linkages established by ICRISAT in relation to simulation modeling included: the IBSNAT project, USA; University of Florida, USA; Michigan State University, USA; IFDC, USA; Indian agricultural universities; Queensland Department of Primary Industries (QDPI), Australia; and ACIAR, Australia. ICRISAT played a pivotal role in developing and adapting these models by acting as a catalyst and linking agricultural research institutes and NARS of the SAT.

At ICRISAT, we have used these crop models for several applications. We have carried out the yield gap analysis of soybean (*Glycine max*), sorghum (*Sorghum bicolor*) and groundnut crops in order to assess the potential for improving productivity in various agro-ecological regions of India. In certain targeted studies, we have also evaluated the agronomic management and climatic risks to the production of these crops. Using sorghum model, nitrogen management strategies for sorghum were also evaluated for the major sorghum growing regions of India, where climatic variability has major influence on response to nutrient inputs. Long-term effects of improved management of a Vertic Inceptisol on potential productivity and water balance of soybean-chickpea and soybean/pigeonpea systems was also completed to assess sustainability in production and the potential of water harvesting and groundwater recharging for providing supplemental irrigation (Singh et al. 2001a, 2001b, 2009).

Results and discussion

Characterization of production systems

Out of the 12 PSs in Asia, India has 10 types of PSs. Further, 12 were delineated in Latin America and 5 in Africa. A PS is defined by the environmental resources, geography, and important issues, or constraints to, and opportunities for improving productivity and sustainable agriculture (ICRISAT 1994).

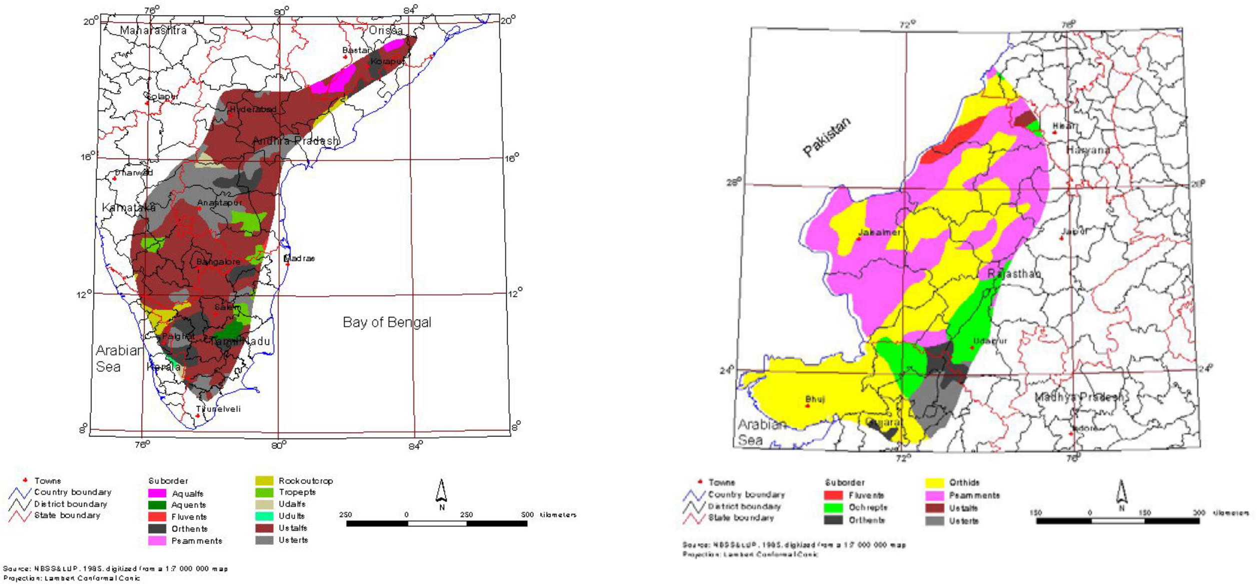
The preliminary definition of these PSs required that they assist in the prioritization essential for development of ICRISAT Medium Term Plans. It also allowed for better focusing of projects to particular PSs and of activities within projects. To identify the target regions and priority areas and allocate resources in the PS research, the ability of GIS, which can analyze multiple layers of information and provide answers spatially, became evident.

Soil being the basis of life on this earth and of course agriculture, information on soil attributes was the most important input variable for any PS assessment. Production system-wise soil attributes were mapped and described to help researchers identify target locations for research and technology transfers. The NBSS&LUP map based on soil taxonomy (Soils of India – suborder associates) (1985) was used in a GIS to provide soil information along with PS boundaries and district boundaries. Area was estimated for each suborder in all the PSs.

Out of the 11 soil orders of soil taxonomy, 7 occur in the 10 PSs in India. The Entisols are the most pervasive of all the soils, and occur in all the PSs. Alfisols (suborder Ustalfs) and Vertisols (suborder Usterts) are found in 8 of the 10 PSs, but Alfisols occupy a total area of 615016 km^2 and Vertisols 470148 km^2 in all the PSs with maximum area (Fig. 3). This helped in understanding the soil types and their attributes in all the PSs of India to appropriately devise technologies and provide more options to farmers of the SAT.

Spatial distribution of rainy season fallows in Madhya Pradesh

As pointed out earlier, a deductive approach including delineation of agricultural land and forests from temporal satellite data was employed to identify fallow in Madhya Pradesh. Three sets of satellite data corresponding to three periods, namely mid-season, late-*kharif* (rainy season) and *rabi* (postrainy season) were used. While mid-season satellite data provides the information on agricultural lands, which were lying unutilized along with those agricultural lands that have been supporting crops, the satellite data of *rabi*, on the other hand, exhibits the spatial distribution pattern of the land supporting crops. These lands include the areas, which were lying fallow during the season, and are now supporting crops. Contrastingly, the satellite data acquired during late



Source: NBSS&LUP, 1985, digitized from a 1:7 000 000 map
Projection: Lambert Conformal Conic

Source: NBSS&LUP, 1985, digitized from a 1:7 000 000 map
Projection: Lambert Conformal Conic

Figure 3. Distribution of different soil orders in the production systems in India.

season show the agricultural lands that were lying fallow during the season and the areas where crops were planted.

It was estimated that 2.02 million ha accounting for 6.57% of the total area of the state were under fallow (Fig. 4). Madhya Pradesh is endowed with well distributed rains ranging from 700 to 1200 mm. Vertisols with good moisture holding capacity can be used to grow short-duration soybean by adopting sound land management practices (Dwivedi et al. 2003). This will help increase income to the farmers besides preventing land degradation due to runoff erosion.

Spatial distribution and quantification of rice-fallows in South Asia – Potential for legumes

Rice, the most extensively grown crop in South Asia, is cultivated on approximately 50 million ha. Despite growing demands for food production because of an increasing population in South Asia, there is little scope for expansion of cropping into new areas and therefore an increase in cropping intensity, along with improvement of yields, needs to take place on existing agricultural lands. Rice-fallows present considerable scope for crop intensification and diversification if the appropriate technology is applied. But there has been limited information on the area of rice-fallows available and on the potential technologies that could be implemented.

This study describes the use of satellite remote sensing and GIS technology to develop an accurate and updated quantification and spatial distribution of rice-fallow lands and a corresponding classification of their potential and constraints for post-rice legumes cultivation in South Asia (Bangladesh, India, Nepal and Pakistan). These rice-fallows represent diverse soil types and climatic conditions and most of these areas appear suitable for growing either cool season or warm season legumes.

Introducing appropriate legumes into rice-fallows is likely to have significant impact on the national economies through increased food security, improved quality of nutrition to humans and animals, poverty alleviation, employment generation, and contribution to the sustainability of these cereal-based PSs in South Asia. This would also provide guidance to policy makers and funding agencies to identify critical research areas and to remove various bottlenecks associated with effective and sustainable utilization of rice-fallows in South Asia.

Satellite image analysis estimated that rice area during 1999 season was about 50.4 million ha. Rice-fallows during 1999/2000 season were estimated at 14.29 million ha in Bangladesh, India, Nepal and Pakistan. This amounts to nearly 30% of the rice-growing area (Fig. 5). These rice-fallows offer a huge potential niche for legumes production in this region. Nearly 82% of the rice-fallows are located in the Indian states of Bihar, Madhya Pradesh, West Bengal, Orissa and Assam. The GIS analysis of these fallow lands has indicated that they represent diverse soil types and climatic conditions; thus a variety of both warm season legumes [such as soybean, mung bean (*Vigna radiata;* green gram), black gram (*Vigna mungo*), pigeonpea and groundnut) and cool season legumes [such as chickpea, lentil (*Lens culinaris*), *khesari* (*Lathyrus sativus*; grass pea), faba bean (*Vicia faba*) and pea (*Pisum sativum*)] can be grown in this region (Subbarao et al. 2001).

An economic analysis has shown that growing legumes in rice-fallows is profitable for the farmers with a benefit-cost ratio exceeding 3.0 for many legumes. Also, utilizing rice-fallows for legume production could result in the generation of 584 million person-days employment for South Asia. The technological components of the rainfed cropping, especially for chickpea crop, have been identified. These include the

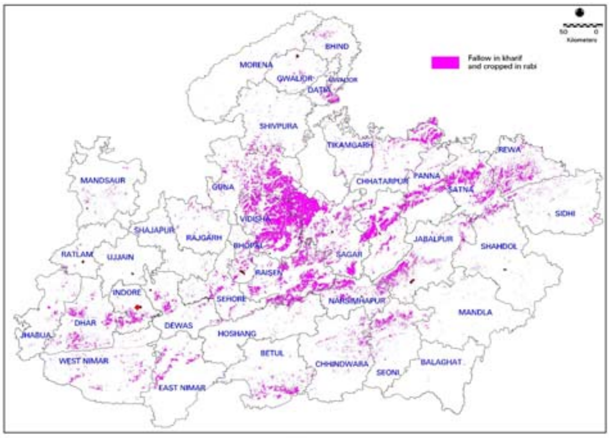


Figure 4. Spatial distribution of rainy season fallows in districts of Madhya Pradesh.

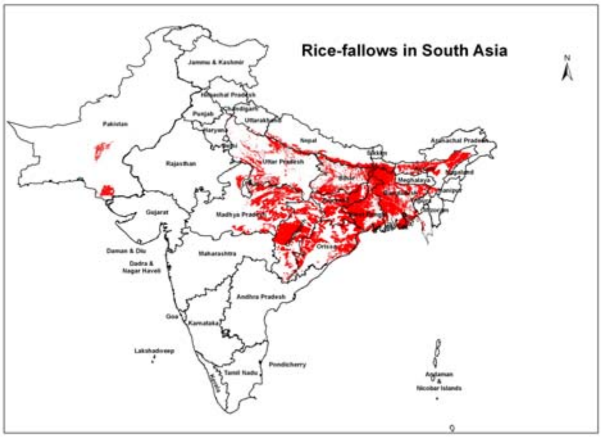


Figure 5. Spatial distribution of rice-fallows in Indo-Gangetic Plains of South Asia.

use of short-duration chickpea varieties, block planting so as to protect the crop from grazing animals, sowing using rapid minimum tillage as soon as possible after harvesting rice, seed priming for 4–6 hours with the addition of sodium molybdate to the priming water at 0.5 g L^{-1} kg^{-1} seed and *Rhizobium* inoculum at 5 g L^{-1} kg^{-1} seed, and application of manure and single superphosphate. Yield of chickpea following rice ranged from 0.4 t ha^{-1} to 3.0 t ha^{-1} across various rice-fallow areas in eastern India. More than six thousand farmers who have been exposed to this technology are now convinced that a second crop can be grown without irrigation in rice-fallows. Similar results have been obtained for the Barind region in Bangladesh. Rainfed cropping in rice-fallow areas increased incomes and improved food security and human nutrition (Subbarao et al. 2001).

Analysis of constraints and potential of the soils of the Indo-Gangetic Plains of Punjab using GIS

Particle size analysis shows that majority of the soils have fine loamy texture, followed by sandy soils. About 12% area of the state is under threat of moderate soil erosion. From this it is obvious that such information gives a better understanding of the quality of the lands of the area. Entisols, Inceptisols and Alfisols are the predominant soils in the state of Punjab.

A case of simple GIS analysis was done to study the changes in wheat (*Triticum aestivum*) productivity in the Indo-Gangetic Plains (IGP) of India. District crop production statistics from the Government of India are used to create the database and then used along with the district map of India in Arc/Info GIS. Wheat productivity from 1960 to 1990 was analyzed in the GIS. The results indicate a steady increase in wheat productivity during this period in the IGP in India with varying degree of enhancement in the yield from 1.5% to as high as 49.5% (Fig. 6). The analysis also reveals that though lower IGP states of West Bengal, Bihar and eastern Uttar Pradesh have lower productivity, higher productivity can be seen in Haryana, Punjab and parts of western Uttar Pradesh. However, negative trends in some districts are due to very high productivity in one year and lower productivity in other years.

Yield gap analysis of rainfed crops for Vietnam, Thailand and India using simulation modeling

In order to assess the capacity of rainfed environments to meet the challenge of future food needs of the growing populations, potential yield and yield gap of major rainfed crops in Thailand, Vietnam and India were assessed. We reviewed the research station experimental data of countries and used crop models to generate information on potential yields and compared with the actual yields at district or province level obtained by the farmers to arrive at yield gap of crops. This analysis

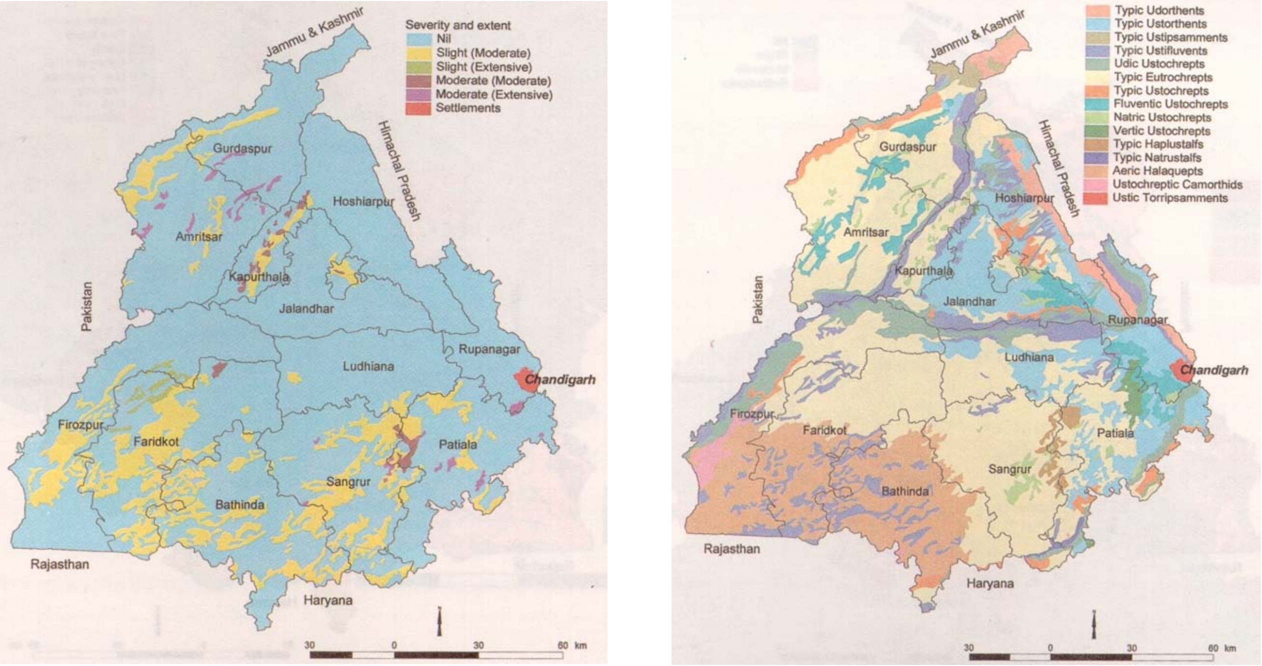


Figure 6. Changes in wheat productivity in the Indo-Gangetic Plains of India.

provided information on the regions/countries and crops where substantial improvements in productivity and production are possible.

Yield gap analysis for northern Vietnam. Vietnam is limited by land area available for increasing food production. Therefore, most of the increase in food production has to come from increasing productivity per unit of land. The major upland crops of northern Vietnam are maize (*Zea mays*), groundnut and soybean. In the mountains, legume crops such as groundnut, soybean and mung bean are grown after rice. These are important sources of protein and oil for the mino-ethnic people, and are used as fodder for cattle and also for improving soil fertility. The major constraints for low yields of rainfed crops in northern Vietnam are undulating topography, poor soil fertility, drought and less adoption of improved soil, water, nutrient, crop and pest management technologies leading to inefficient use of natural resources such as rainfall. At present the crop yields in northern Vietnam are low: 3.3 t ha^{-1} for maize, 1.52 t ha^{-1} for groundnut and 1.36 t ha^{-1} for soybean. The crop simulation analysis showed that soybean yields can be increased by 1.5 to 1.7 times, groundnut yields by 2.3 to 2.7 times and maize yields by 2.7 to 3.0 times from their current level of productivity in the six selected provinces during the spring and summer or autumn-winter seasons (Table 1). Production can be increased by 0.06 to 0.10 million t for soybean, 0.18 to 0.32 million t for groundnut and 0.96 million t for maize in northern Vietnam (Singh et al. 2001a).

Yield gap analysis for northeastern Thailand. Northeastern Thailand covers about 17 million ha or one-third of the whole country. Agriculture in Northeast (NE) Thailand is based mainly on upland crops that require less water, such as cassava (*Mannihot esculenta*), upland rice, sugarcane (*Saccharum officinarum*), maize, soybean, groundnut and sunflower (*Helianthus annuus*), which are important crops of this region. Major constraints that limit the yield of crops are frequent droughts and floods, low soil fertility, soil erosion and land degradation, poor soil water conservation practices, low-yielding crop varieties and poor socioeconomic condition of farmers. The current level of productivity in NE Thailand is 1.75 t ha^{-1} for upland rice, 2.45 t ha^{-1} for maize, 1.2 t ha^{-1} for soybean, 1.34 t ha^{-1} for groundnut and 1.47 t ha^{-1} for sunflower (Table 2). The experimental yields observed were 1.2 times more for upland rice, 1.9 times for maize, 1.7 times for soybean and 1.3 times for groundnut indicating the potential for yield improvement. Expected yield improvements for sunflower in the region are very negligible. Considering the yield gaps and current area under each crop, production of rice can be increased by 8.1 million t, maize by 0.83 million t, soybean by 0.043 million t and groundnut by 0.012 million t (Singh et al. 2001a).

Yield gap analysis for India. Dominant rainfed crops in India are sorghum, pearl millet, pigeonpea, chickpea, soybean and groundnut. The analysis showed that substantial yield gaps exist between the current level of farmers' yields and the experimental or simulated

Table 1. Yield gap analysis of rainfed crops in northern Vietnam[1]**.**

Crop	Area (million ha)	Season	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Rainfed potential yield (t ha^{-1})	Yield gap (t ha^{-1})
Soybean	0.12	Spring	1.36	1.77	2.00	0.40–0.68
		Summer	1.36	1.96	2.35	0.6–1.01
Groundnut	0.14	Spring	1.52	3.0	4.17	1.50–2.60
		Autumn-winter	1.52	2.62	3.53	1.1–2.0
Maize	0.53	Spring	3.3		5.0	1.65
		Summer	3.3		5.3	1.99

1. Source: Singh et al. (2001a)

Table 2. Yield gap analysis of rainfed crops in Northeast Thailand.

Crop	Area (million ha)	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Yield gap (t ha^{-1})
Rice	4.55	1.75	3.53	1.78
Maize	0.37	2.45	4.70	2.25
Soybean	0.06	1.20	1.91	0.71
Groundnut	0.04	1.34	1.73	0.29
Sunflower	0.01	1.47	1.60	0.13

potential yields. The cereal yields (pearl millet and sorghum) can be increased 2.7 to 3.0 times with improved management. The yields of the legumes and oilseeds can be increased 2.3 to 2.5 times from the current level of productivity (Table 3). Further increase in yield of these crops is possible with supplemental irrigation to the rainfed crops**.** Production of sorghum can be increased by 4.6 to 9.8 million t, pearl millet by 12.1 to 13.3 million t, pigeonpea by 3.1 to 3.4 million t, chickpea by 5.8 to 7.8 million t, soybean by 7.4 to 7.7 million t and groundnut by 6.6 to 10.8 million t (Singh et al. 2009).

In addition to the analysis of potential productivity and yield gaps, we have also carried out the analysis of soil water balance of various AEZs where major rainfed crops in Thailand, Vietnam and India are grown. The opportunities available for harvesting of surface runoff and groundwater recharging have been established for providing supplemental irrigation to the crops or to extend the growing season.

Crop and land management practices and soil carbon sequestration

Crop models incorporating soil carbon balance have been used to identify the soil and crop management practices that will sequester more carbon in the soil, thereby improving soil fertility and mitigating the impacts of climate change in the long run. Long-term simulation of soil carbon dynamics for the Vertic inceptisol showed that in spite of continuous decline in organic carbon (OC) of soil after clearing the fields of natural vegetation and grasses, the OC retention in the soil was consistently higher with the addition of crop residues in the soybean/pigeonpea intercrop system as compared to the soybean-chickpea sequential system. Simulation results also showed that addition of crop residues (C:N ratio 16:1) at 8 t ha^{-1} yr^{-1} would be required to maintain soil OC at the initial levels observed at the beginning of the study.

Assessment of seasonal rainfall forecasting and climate risk management options for peninsular India

Uncertainty of the climate and weather have adverse effects on crop production and income of the farmers in the SAT. They are traditionally risk averse and conservative in adopting high input improved technologies because of the uncertainties in production associated with variable climate. Seasonal climate prediction before onset of the season could help them in taking appropriate decisions to minimize losses in low rainfall years and harness the potential in the normal or high rainfall years. With the technical input from the International Research Institute on Climate Prediction, a pilot project was carried out in Nandyal and Anantapur in Andhra Pradesh to assess the value and benefit of seasonal climate prediction at district scale to the farmers. Using GCM predictor-based model output statistical (MOS) technique, the probabilistic seasonal rainfall prediction for the year 2003 was communicated to the farmers at a lead time of more than a month to take up appropriate cropping decisions for the two districts. Seasonal climate prediction for Nandyal proved accurate and the farmers derived significant benefit by adopting double cropping in the region as compared to the single crop. Farmers in Anantapur had mixed experience as the rains started late in the district. The farmers who adopted groundnut/short-duration pigeonpea intercrop were benefited and those who followed groundnut/medium-duration pigeonpea intercrop incurred losses as compared to the sole groundnut system. This work will be further strengthened in the next five years.

Table 3. Yield gap analysis of crops in India[1].

Crop	Area (million ha)	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Rainfed potential yield (t ha^{-1})	Yield gap (t ha^{-1})
Kharif sorghum	5.43	1.14	3.50	3.50	2.31
Rabi sorghum	5.45	0.62	2.40	1.50	0.85–1.8
Pearl millet	9.77	0.71	2.07	1.95	1.24–1.36
Pigeonpea	3.36	0.61	1.62	1.52	0.91–1.01
Chickpea	7.28	0.77[2]	1.85[2]	1.08	0.8–1.07
Soybean	6.3	0.98	2.16	2.24	1.18–1.23
Groundnut	6.6	1.03	2.03	2.66	1.0–1.63

1. Source: Singh et al. (2009)
2. With supplemental irrigation.

Remote sensing and GIS-based model for estimating soil loss from watersheds

Remote sensing and GIS-based techniques are essential for large-scale implementation and monitoring of watershed program. Remote sensing data based soil erosion model was used for estimation of sediment yield and runoff from an agricultural watershed in Medak district of Andhra Pradesh. The basic data was derived from panchromatic sensor (PAN) stereo data of Indian Remote Sensing Satellite IRS-1C as well as aerial photographs. The input parameters required for the model were also derived through visual interpretation of aerial photographs. The slope factor was derived from digital elevation model (DEM) generated from the aerial photographs and PAN stereo images. A comparison of elevation and slope derived from PAN stereo images and aerial photographs reveal that the latter has an edge over the former with respect to information on elevation and those obtained from in-situ measurement have been found to be in good agreement. The initial results from the GIS and remote sensing based technique for topographic survey and estimating runoff and soil loss are quite good. However, some more testing and validation under various topographic conditions is needed.

Biophysical characterization of watersheds and regions

Understanding the distribution and magnitude of biophysical resources of watersheds is required to develop technology intervention plans for the management of natural resources and to increase agricultural productivity in an area. During the five-year period, we characterized the agroclimatic and other biophysical resources such as soils and vegetation resources of the watersheds, which helped in planning as well as in quantifying the impacts made during the project period as well as at the termination of the projects.

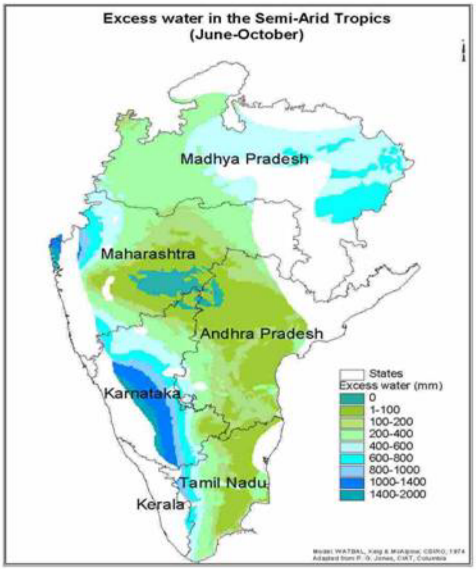


Figure 7. Excess water available for harvesting as runoff in June–October in the states of SAT India**.**

Regional-scale water budgeting for SAT India. For prioritization and selection of target regions for watershed development, first-order water budgeting using GIS-linked water balance model was used for the selected states in central and peninsular India. Such a simulation model used with monthly rainfall and soils data generated outputs that can be effectively used to prioritize the regions and strategies for improved management of rainwater (Fig. 7).

Once the target region is selected, then the selection of appropriate benchmark sites using second-order water budgeting with more detailed simulation models can be applied. The GIS map produced using this methodology shows the potential of various regions in central and peninsular India for the amount of water surplus available for water harvesting and groundwater recharging.

Table 4. Annual water balance characters at different locations[1].

Country	Location	Rainfall (mm)	PET (mm)	AET (mm)	WS (mm)	WD (mm)
China	Xiaoxingcun	641	1464	641	Nil	815
	Lucheba	1284	891	831	384	60
Thailand	Wang Chai	1171	1315	1031	138	284
	Tad Fa	1220	1511	1081	147	430
Vietnam	Chine	2028	1246	1124	907	122
	Vinh Phuc	1585	1138	1076	508	62
India	Bundi	755	1641	570	186	1071
	Guna	1091	1643	681	396	962
	Junagadh	868	1764	524	354	1240
	Nemmikal	816	1740	735	89	1001
	Tirunelveli	568	1890	542	Nil	1347

1. PET = Potential evapotranspiration; AET = Actual evapotranspiration; WS = Water surplus; WD = Water deficit.

Water balance of watersheds in China, Thailand, Vietnam and India. Weekly water balances of selected watersheds in China, Thailand and Vietnam were completed based on long-term agrometeorological data and soil type. The water balance components included PET, AET, water surplus and water deficit. PET varied from about 890 mm at Lucheba in China to 1890 mm at Tirunelveli in South India (Table 4). AET values are relatively lower in the watersheds in China and India compared to those in Thailand and Vietnam. Varying levels of water surplus and water deficit occur in the watersheds. Among all the locations, Tirunelveli in India has the largest water deficit (1347 mm) level and no water surplus. Chine in Vietnam has the largest water surplus level of 907 mm. These analyses defined the dependability for moisture availability for crop production and opportunities for water harvesting and groundwater recharge.

Spatial water balance modeling of watersheds. In partnership with the Michigan State University, USA, we have attempted to integrate the topographic features of the watersheds with the hydrological models. The automation of the terrain analysis and the use of digital elevation models have made it possible to quantify the topographic attributes of the landscape for hydrological models. These topographic models, commonly called digital terrain models, partition the landscape into 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 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 soil watershed (BW 7) on-station experiment at ICRISAT, Patancheru, India was used for validating the model developed at Michigan State University. This partnership research led to the development of SALUS-TERRAE, a digital terrain model for predicting the spatial and temporal variability of soil-water balance. A regular grid digital elevation model provided the elevation data for SALUS-TERRAE. We have successfully applied the SALUS-TERRAE, which was a functional spatial soil-water balance model, at a field scale to simulate the spatial soil-water balance and identified how the terrain effects the water routing across the landscape. The model provided excellent results as compared with the field-measured soil-water content (Fig. 8).

The project “Improving Management of Natural Resources for Sustainable Rainfed Agriculture” (RETA 5812) was executed by ICRISAT by adopting a consortium approach for technical backstopping of the community watersheds. The targeted ecoregion is characterized by assured annual rainfall of 700–1300 mm with medium to high water holding capacity soils. Five benchmark watersheds in India, NE Thailand and northern Vietnam covering the target ecoregion were selected to develop and test the holistic farmer participatory integrated watershed development model with the aim of increasing agricultural productivity on sustainable basis while minimizing land degradation for improving the rural livelihoods. All the five benchmark watersheds in Asia were characterized for socioeconomic parameters by adopting rapid rural appraisals (RRAs) and detailed household surveys using stratified sampling method. The results of biophysical, socioeconomic characterization as well as inputs and crop productivity are discussed supported by GIS maps for the available natural resources (Wani and Ramakrishna 2005).

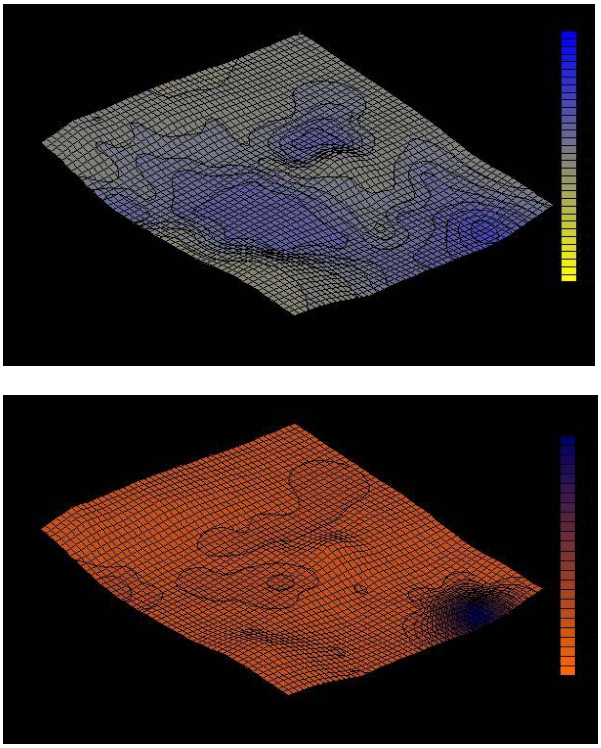


Figure 8. Soil-water content (cm) on day-2 for scenario 1 (uniform soil type, high rainfall, no restricting soil layer) in the top 0–26 cm soil depth (top); and 26–77 cm soil depth (bottom).

Improving management of natural resources for sustainable rainfed agriculture

A geospatial characterization was done for the Adarsha watershed, Kothapally, Andhra Pradesh by collecting baseline information on different agroclimatic and socioeconomic variables and constraints. Village-level maps were prepared for land use, crops, soils and cropping systems every year. The results of the survey indicated that in Kothapally village the dryland area was more (62.79%) compared to irrigated land (37.21%); literacy rate was very low (35.74%) and labor was scarce. Also there were no options for income generation. Crop yields were very low and there were no soil and water conservation structures (Wani et al. 2003c).

Similar characterizations were done for Lateri watershed in Vidisha district, Rignodia watershed in Indore district of Madhya Pradesh in India, Tad Fa watershed in Khon Kaen province of Northeastern Thailand and Thanh Ha watershed in Hao Binh province of Vietnam to understand the agroecological potential and associated constraints to achieve the potential gains.

After ICRISAT interventions are in place, the impact of watershed management can be seen by continuous monitoring of all the selected parameters. To monitor the groundwater levels 64 open wells in the watershed were geo-referenced and regular monitoring of water level and quality was done. At Kothapally watershed, throughout the season higher groundwater levels were recorded from the well near the major check-dam compared to water levels in wells away from the check-dam. This clearly shows the effectiveness of the improved watershed technologies in increasing the groundwater recharge thereby improving the availability of water for agricultural and other uses (Wani et al. 2003c).

Integrated watershed management for land and water conservation and sustainable agricultural production in Asia

The PAN and LISS III merged image of the IRS satellite was used to create land use/land cover, slope, drainage network, land irrigability erosion intensity and groundwater prospectus of Malleboenpally, a drought prone watershed in Andhra Pradesh.

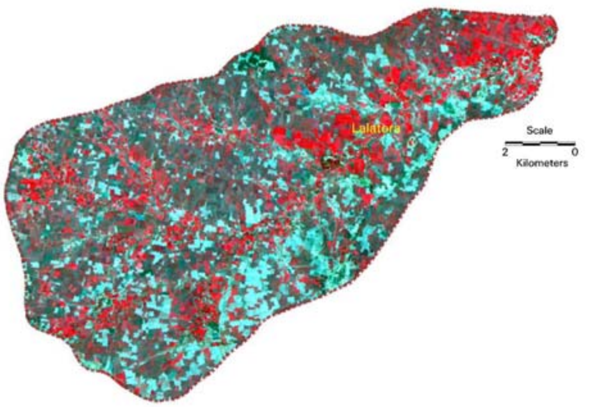


Figure 9. NDVI of Milli watershed in 1997 postrainy season.

Limited natural resources, erratic rainfall, land degradation, soil erosion, poverty and burgeoning population characterize the dry regions in Asia. Over-exploitation of natural resources in these areas to meet the ever-increasing demand for food and fuel of rapidly growing population has led to environmental degradation and calls for initiation of immediate steps for optimal utilization of natural resources based on the potential and limitations. Information on the nature, extent, and spatial distribution of natural resources is a prerequisite for achieving this goal. Multispectral measurements made at regular intervals using satellites hold immense potential of providing such information in a timely and cost-effective manner, and facilitate studying the dynamic phenomenon that helps in assessing the effectiveness of the interventions made in the benchmark watersheds. Integration of remotely sensed data in GIS along with simulation models would increase our ability to conceptualize, and develop strategies to manage the natural resources in the watersheds efficiently on sustainable basis.

In partnership with the National Remote Sensing Agency (NRSA), Hyderabad, Indian remote sensing satellites (IRS-1B/-1C and -1D) data is used for developing and managing watersheds efficiently as well as for monitoring the impact of various interventions made in the watersheds in 1997.

The Milli watershed in Lateri Block is located in the northwest corner of Vidisha district in Madhya Pradesh in central India. This watershed consists of 35 villages, which are grouped into 17 micro-watersheds. The Lalatora micro-watershed (725 ha) was selected for detailed monitoring of hydro-meteorological measurements. The change in biomass is reflected in the agricultural land use. The agricultural land use of Milli watershed was mapped using the satellite data and added into a GIS database. Since the soil and water conservation measures were initiated during 1997, IRS-1C LISS-III data for postrainy season of 1997 was used to derive information on agricultural land use before the watershed activities were initiated in this area (Figs. 9 and 10). To study the impact of the program on the land use, IRS-1C LISS-III data of 2001 was used (Fig. 11). This analysis using remotely sensed data by satellite provided direct evidence in increased cultivation during postrainy season. Such an increase in area during postrainy season is mainly due to increased water availability in soil or in wells, which helped the farmers to increase their cultivated area.

In partnership with NRSA, vegetation cover was studied by generating the Normalized Difference Vegetation Index (NDVI), which is essentially the ratio of the differences of the response in the near infrared and red regions of the spectrum. Their sum values thus obtained range normally between 0 and 1.0. However, values of NDVI less than zero are also encountered which indicate barren or fallow land.

The NDVI images generated from LISS-III data of 1997 and 2001 indicate a marginal increase in the vegetation cover supporting thereby the observation made on the agricultural land use. An estimated 31.5% of the geographic area of watershed has been found to be in the NDVI range of 0.10–0.55 in 1997, but it has risen to 40.3% during 2001 demonstrating an increase of 9% in the greenery in the watershed. It is, indeed, interesting to note that in Lalatora micro-watershed where the soil and water conservation treatments have been imposed, the vegetation cover has improved tremendously. As against only 149 ha of vegetation cover during 1997–98, it has risen to 229 ha during 2000–01 registering thereby an increase of 80 ha during 3-year period (Wani et al. 2003b).

Shruthi (2004) has used remote sensing and GIS for groundwater prospecting in agricultural watersheds of Madhya Pradesh and eastern Rajasthan, India. Multiple thematic layers were derived from the multispectral remote sensing data from the Indian remote sensing satellite (IRS-P6, LISS IV sensor). These thematic layers were integrated in a GIS to delineate groundwater potential zones and suitable sites for groundwater recharge. Milli and Guna watersheds in Madhya Pradesh and Bundi watershed in Rajasthan were studied representing different landscapes. Sandhya (2004) used remote sensing and GIS to estimate runoff in small

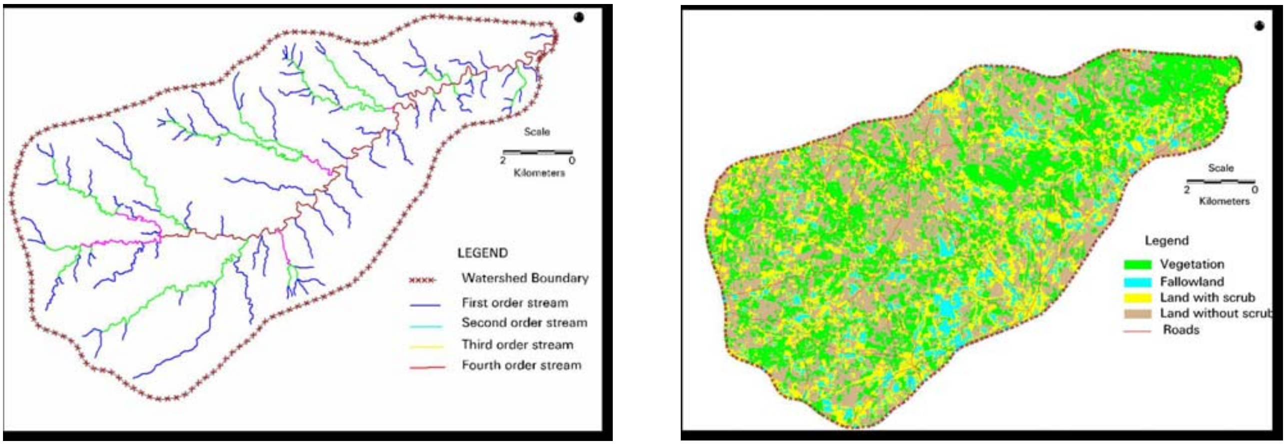


Figure 10. Drainage network and land use cover in Milli watershed of Vidisha district in Madhya Pradesh.

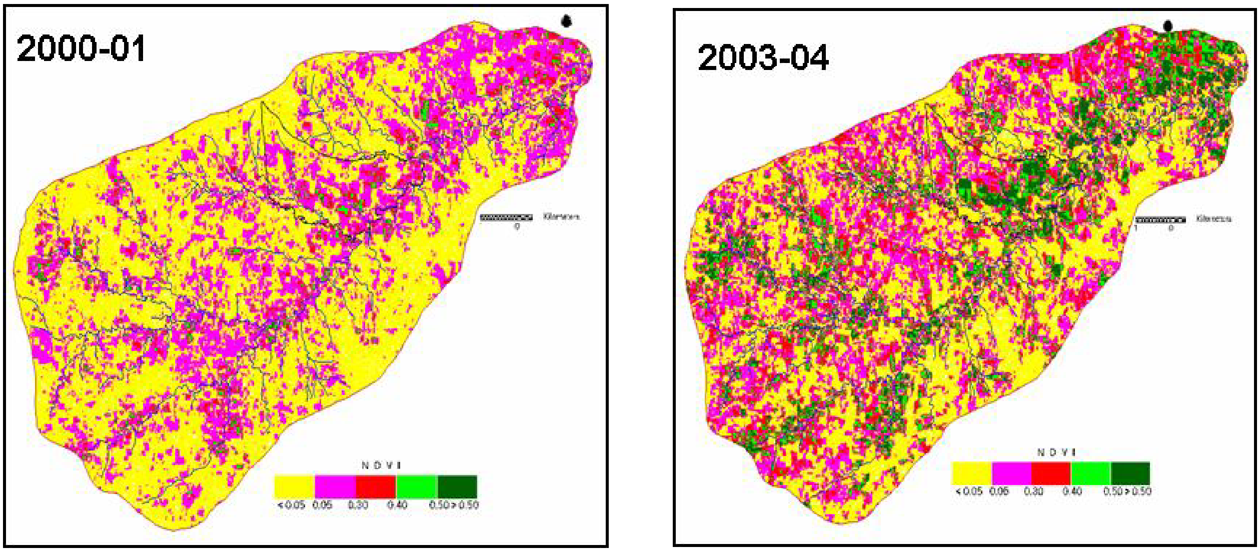


Figure 11. NDVI of Milli watershed in Lalatora in 2000–01 and 2003–04.

agricultural watersheds of Madhya Pradesh and Rajasthan. Thematic maps were generated using remotely sensed data and Survey of India topographic sheets (Fig. 12). The USDA-SCS method is used for runoff estimation. Leya (2005) also studied the same watersheds for the impact of the integrated watershed management program.

Use of satellite data for watershed management and impact assessment

Adarsha watershed in Kothapally is bound by geo-coordinates 17°21’ to 17°24’ N and 78°5’ to 78°8’ E and forms part of Shankarpally mandal (an administrative unit) of Ranga Reddy district, Andhra Pradesh, India. Vertisols and associated Vertic soils occupy 90% of the watershed area. However, Alfisols do occur to an extent of 10% of the watershed area. The main (rainy season) crops grown are sorghum, maize, cotton (*Gossypium* sp), sunflower, mung bean (green gram) and pigeonpea. During (postrainy season) wheat, rice, sorghum, sunflower, vegetables and chickpea are grown (Fig. 13). The mean annual rainfall is about 800 mm, which is received mainly during June to October.

Thematic maps were prepared by enhancing the low resolution multispectral data with high resolution panchromatic data by a process of merging on hydrogeomorphological conditions, soil resources, and present land use/land cover have been generated through a systematic visual interpretation of IRS-1B/-1C/-1D LISS-II and -III data in conjunction with the collateral information in the form of published maps, reports, wisdom of the local people, etc supported by ground-truth. The information derived on the lithology of the area and geomorphic and structural features in conjunction with recharge condition and precipitation was used to infer groundwater potential of each lithological unit.

In addition, derivative maps, namely, land capability and land irrigability maps were generated based on information on soils and terrain conditions according to criteria from the All India Soil and Land Use Survey Organization (All India Soil and Land Use Survey 1970). Land use/land cover maps have been prepared using monsoon and winter crop growing seasons and summer

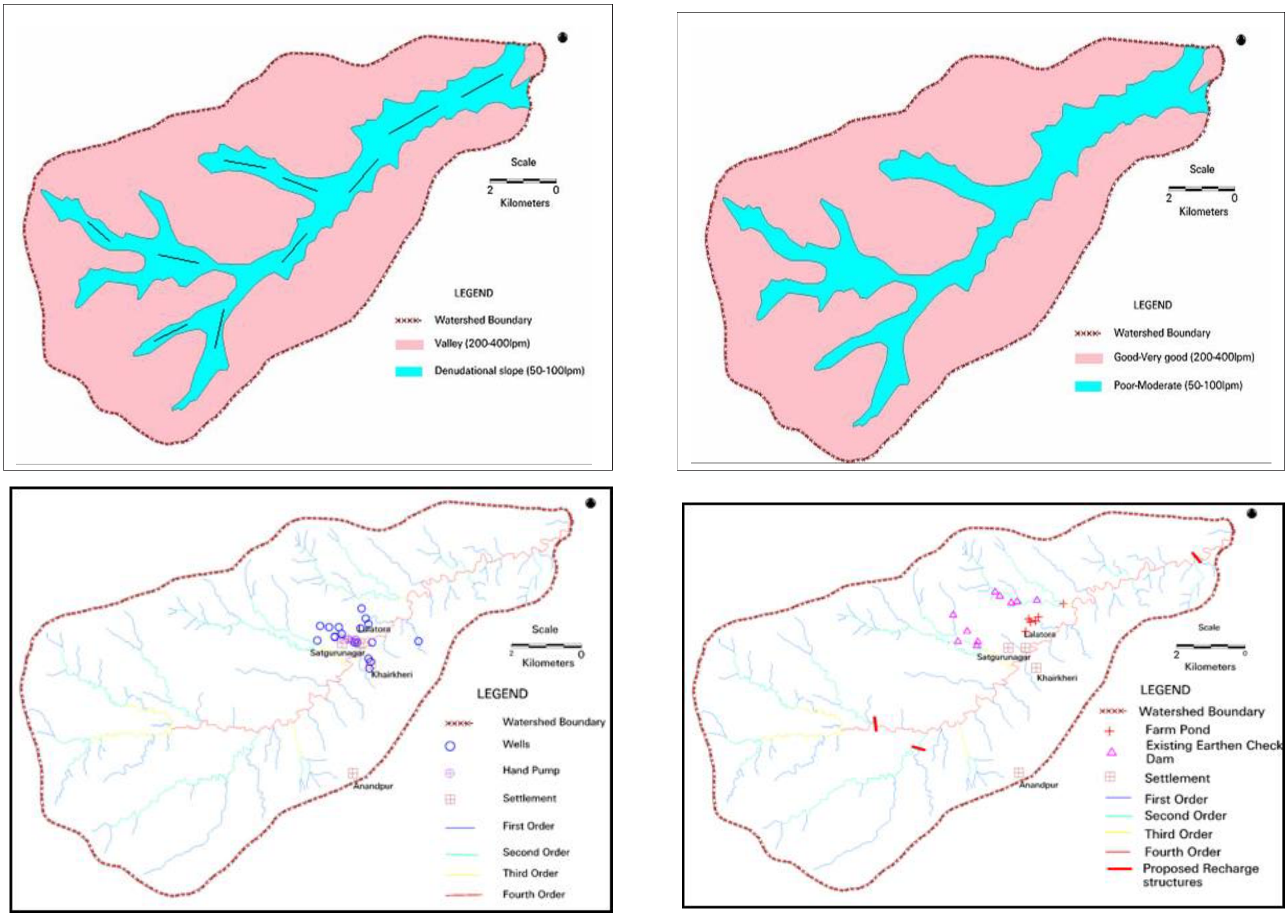


Figure 12. Thematic maps depicting drainage network, location of water conservation structures and groundwater prospectus in Milli watershed, Vidisha in Madhya Pradesh.

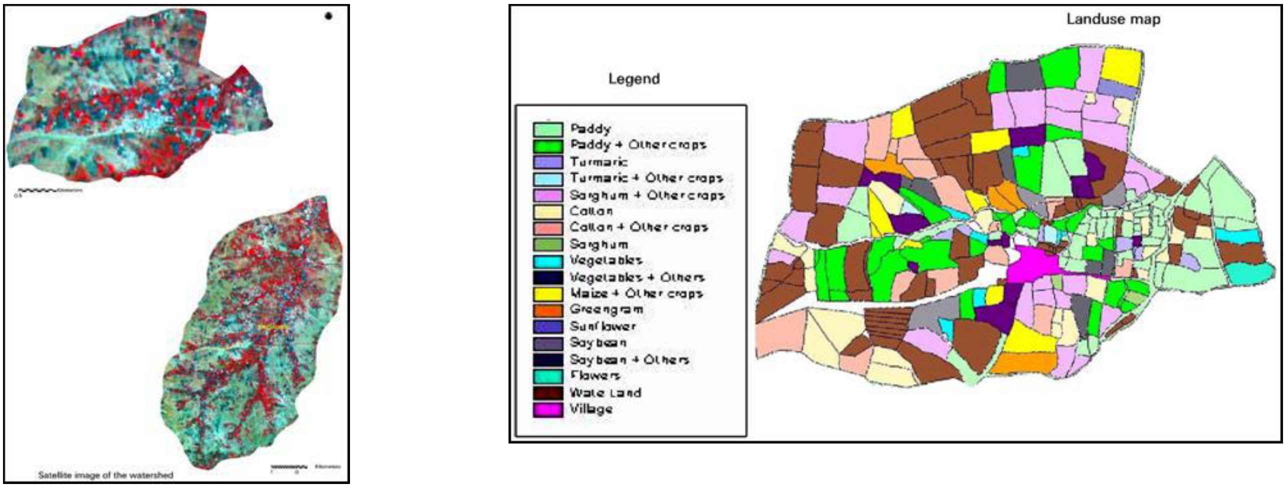


Figure 13. Adarsha watershed, Kothapally, Andhra Pradesh, India: Satellite image (left) and GIS map showing cropping pattern (right).

period satellite data for delineating single-cropped and double-cropped areas apart from other land use and land cover categories. Furthermore, micro-watersheds and water bodies have been delineated and the drainage networks have also been mapped (Fig. 14). Slope maps showing various slope categories have been prepared based on contour information available at 1:50,000 scale topographical sheets. Rainfall data were analyzed to study the rainfall distribution pattern in time and space. Demographic and socioeconomic data were analyzed to generate information on population density, literacy status, economic backwardness and the availability of basic amenities.

The generation of an action plan essentially involved a careful study of thematic maps on land and water resources, both individually as well as in combination, to identify various land and water resources regions or Composite Land Development Units (CLDU) and their spatial distribution, potential and limitations for sustained agriculture and other uses, and development of an integration key. It was achieved in a GIS domain using ARC/INFO version-7 software. Each CLDU was studied carefully and a specific land use and soil and water conservation practice was suggested based on its sustainability. Subsequently, taking landform as a base an integration key in terms of potential/limitations of soils, present land use/land cover and groundwater potential, and suggested alternate land use/action plan were developed.

Since the watershed very often experiences drought, apart from alternate land use based on potential and limitations of natural resources, various drought proofing measures such as vegetative barriers, contour bunding, stone check-dams, irrigation water management, horticulture, groundwater development with conservation measures, and silvipasture in marginal lands have been undertaken (Fig. 15). The suggested optimal land use practices are intensive agriculture, intercropping system, improved land configuration, agro-horticulture, horticulture with groundwater development and silvipasture. Soon after implementation of the suggested action plan, the area undergoes transformation, which is monitored regularly. Such an exercise not only helps in studying the impact of the program, but also enables resorting to mid-course corrections, if required. Parameters included under monitoring activities are land use/land cover, extent of irrigated area, vegetation density and condition, fluctuation of groundwater level, well density and yield, cropping pattern and crop yield, occurrence of hazards and socioeconomic conditions. Land use/land cover parameters include: changes in the number and aerial extent of surface water bodies, spatial extent of forest and other plantations, wastelands and cropped area.

NDVI has been used to monitor the impact of the implementation of action plan. NDVI images of 1996 and 2000 reveal an increase in the vegetation cover, which is reflected in improvement in the vegetation cover. The spatial extent of moderately dense vegetation cover, which was 129 ha in 1996, has risen to 152 ha in 2000. Though the satellite data used in the study depicts the terrain conditions during 1996, implementation activities started only in 1998. It is, therefore, obvious that it will take considerable time for detectable changes in the terrain and vegetation conditions (Dwivedi et al. 2003) (Fig. 16).

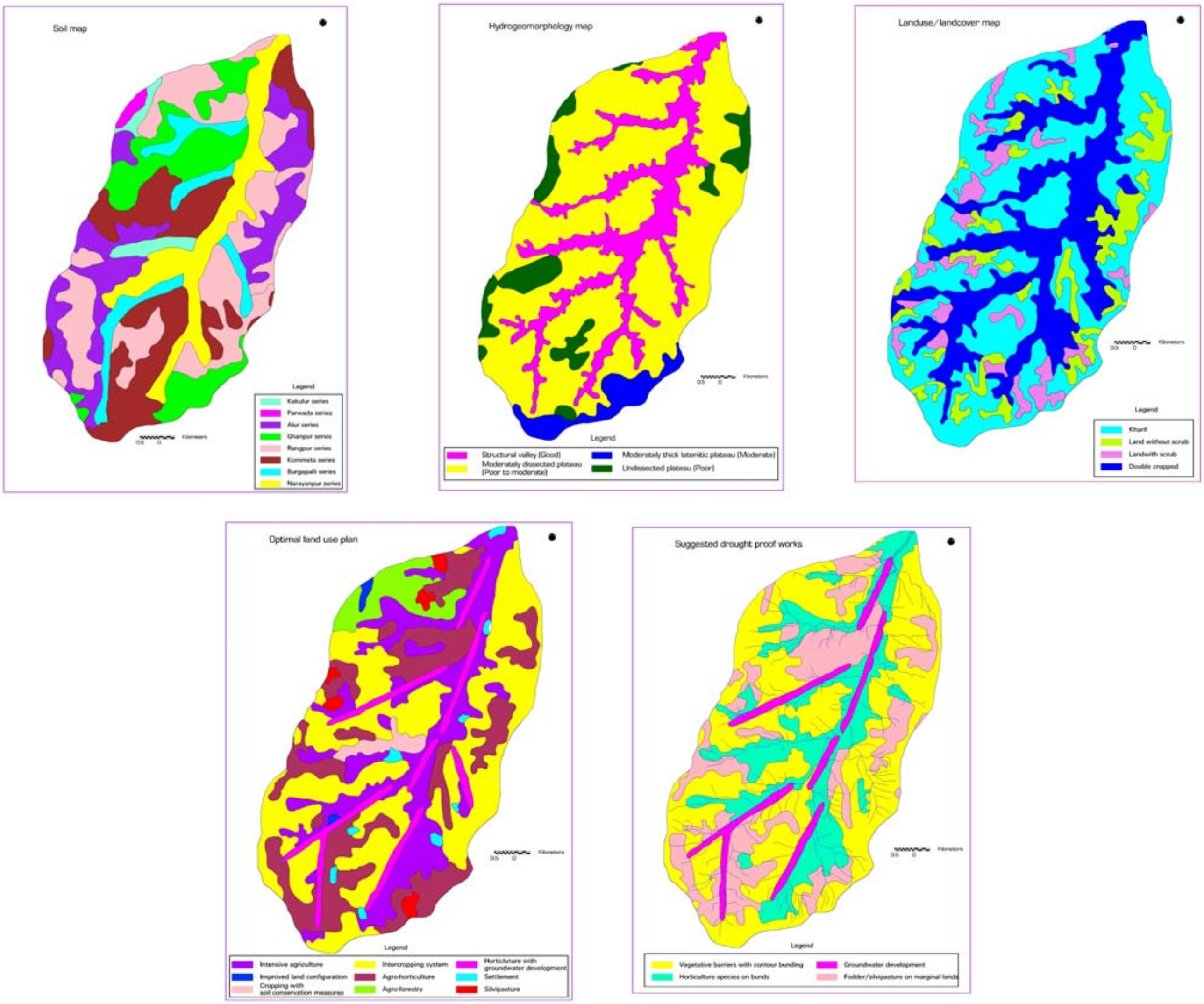


Figure 14. Thematic maps depicting soils, land use pattern and proposed drought proofing measures in Adarsha watershed, Kothapally, Andhra Pradesh, India.

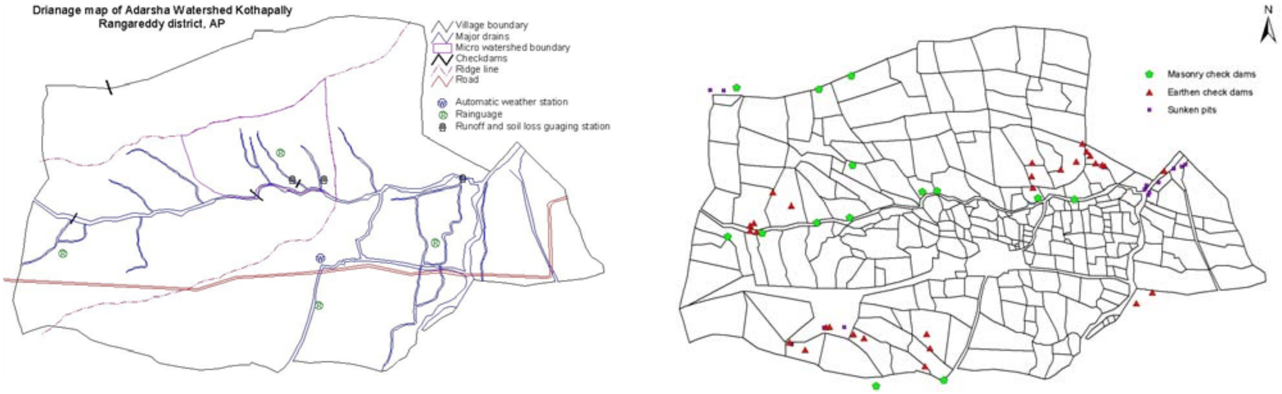


Figure 15. GIS map of Adarsha watershed depicting drainage network and location of water conservation structures in Adarsha watershed, Kothapally, Andhra Pradesh, India.

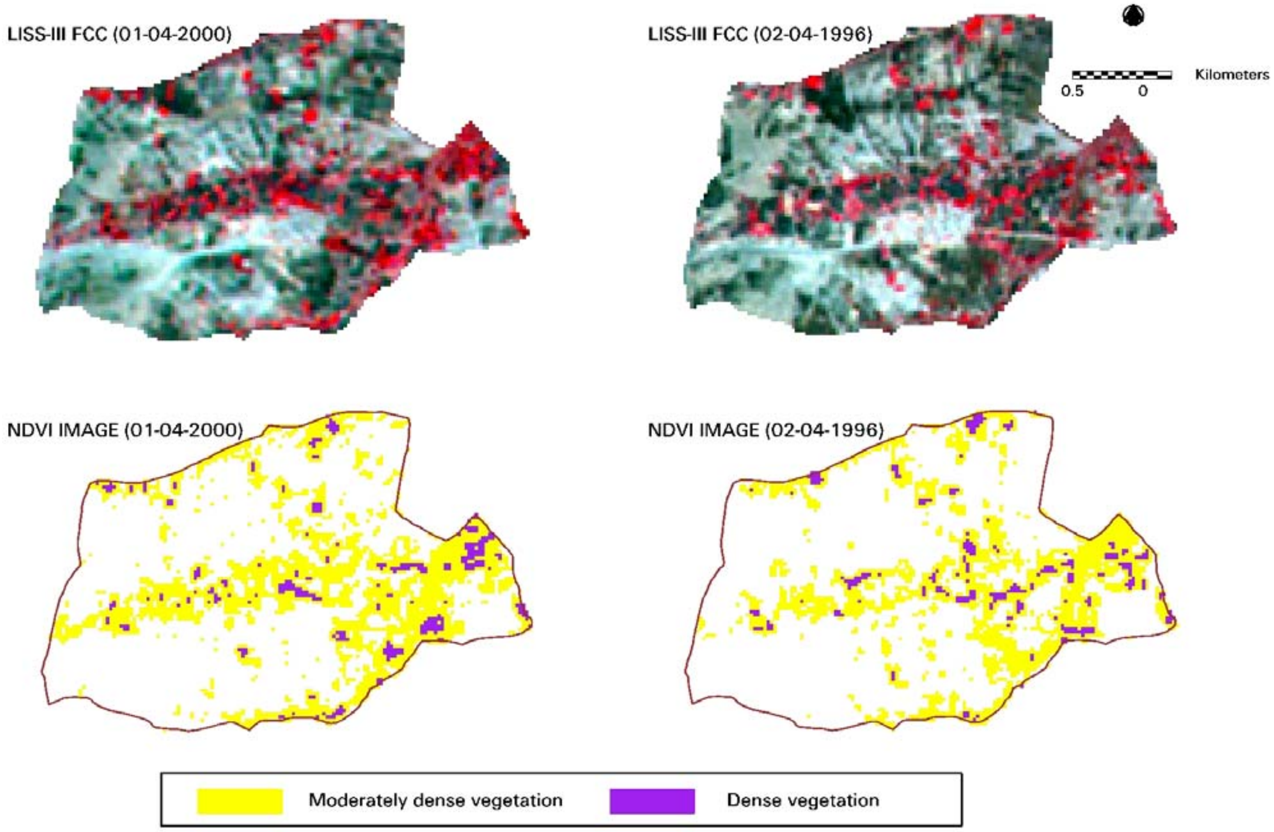


Figure 16. Satellite and NDVI images of Adarsha watershed, Kothapally, Andhra Pradesh, India.

Using GIS and survey data, the watersheds in India, Thailand and Vietnam were characterized for the distribution of natural resources like soils, climate, water resources and land use systems at the initiation of the watershed projects. In India, the watersheds in Andhra Pradesh (Kothapally, Malleboenpally, Appayapalli, Tirumalapuram, Nemmikal and Kacharam) and Madhya Pradesh (Lateri and Rignodia) were characterized; also Tad Fa watershed in Thailand and Thanh Ha watershed in Vietnam were characterized. Using remote sensing and GIS technology, we have observed significant improvements in the vegetation cover in Kothapally watershed in Andhra Pradesh and Lateri watershed in Madhya Pradesh with the introduction and adoption of improved resource management and crop production technologies over the period of five years.

Summary and conclusion

Use of new science tools in rainfed agriculture open up new vistas for development. It will help in improving the rural livelihoods and contributing substantially to meet the millennium development goals of halving the number of hungry people by 2015. Till now rainfed areas of the SAT did not get much benefit of new science tools but the recent research using these tools such as simulation modeling, remote sensing, GIS as well as satellite-based monitoring of the natural resources in the SAT has shown that not only the effectiveness of the research is enhanced substantially but also the cost efficiency and impact are enhanced. By using crop simulation modeling approach yield gap analyses for the major crops in India revealed that the yields could be doubled with the existing technologies if we could scale-out the new management options. Similarly, technology application domains could be easily identified for better success and greater adoption of the particular technologies considering the biophysical as well as socioeconomic situations. The GIS systems helped in speedy analysis of voluminous data and more rationale decision in less time to target the investments as well as to monitor the large number of interventions in the country. The satellite-based techniques along with GIS helped in identifying the vast fallow areas (2 million ha) in Madhya Pradesh during the rainy season. Similarly, 82% of 14 million ha rice-fallows in the IGP are in India and offer excellent potential to grow second crop on residual soil moisture by using short-duration chickpea cultivars and simple seed priming technology. These techniques are also successfully used for preparing detailed thematic maps, watershed development plans and continuos monitoring of the natural resources in the country in rainfed areas. In brief, by applying new science tools, productivity as well as income from rainfed agriculture could be substantially improved and thus livelihoods of the rural people could also be improved.

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