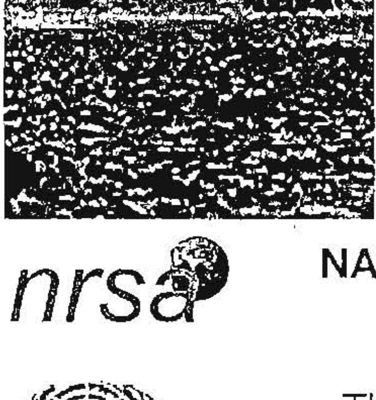
LECTURE NOTES

REGIONAL WORKSHOP ON AGRICULTURAL DROUGHT MONITORING AND ASSESSMENT USING SPACE TECHNOLOGY

May 3-7, 2004



nrsa

NATIONAL REMOTE SENSING AGENCY
(Dept. of Space, Govt. of India)
and
THE UNITED NATIONS ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND PACIFIC

COMBATING DROUGHT THROUGH INTEGRATED WATERSHED MANAGEMENT FOR SUSTAINABLE DRYLAND AGRICULTURE

S.P. WANI, S.S. BALLOLI, A.V.R. KESAVA RAO AND T.K. SREEDEVI

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India

Abstract

In a country like India, where 69% of arable land is rainfed, drought is a constant threat in one or another part of country. Drought is a recurring phenomenon and we need to manage drought effectively using the new knowledge and technology rather than dealing with as a disaster. Historical weather data helps in understanding the patterns of drought occurrence as well as establishing the length of the growing season and fitting the suitable cropping systems accordingly. The nexus between drought, land degradation and poverty could be broken by adopting integrated watershed development approach. The ICRISAT and partners developed an innovative farmer participatory consortium model for efficient and sustainable management of natural resources in the watersheds. The approach adopted is integrated genetic and natural resource management (IGNRM) and watersheds are used as entry points for improving the livelihoods. The results of a case study and scaling-up activities under the Andhra Pradesh Rural Livelihoods Program are discussed.

Introduction

The Indian agriculture sector, which provides nearly 28% to the GDP of the country, is largely affected by droughts. In the SAT, due to the large year-to-year variation in the amount and distribution of rainfall, occurrence of drought is inevitable. Basic requirement for drought management is drought characterization and monitoring. There are five distinct categories of drought affecting crop production. These are 1)Early-season drought, 2) Mid-season drought, 3)Late-season or terminal drought, 4)Apparent drought and 5)Permanent drought

Early-season droughts occur in association with the delay in commencement of sowing rains. Mid-season droughts occur in association with the breaks in the southwest monsoon. Late season or terminal droughts are associated with the early cessation of rainy season and may lead to increase in temperature, hastening crop development and forced maturity. Apparent drought conditions prevail due to the mismatching of cropping patterns to rainfall in some regions. Permanent drought conditions are common in arid regions and even the drought-resistant crops may fail in certain years.

Droughts have a major impact on the agricultural economy and the underlying natural resources of the region. Both cropland and forestland are affected by drought. Many a time, the land degradation problems are aggravated by drought due to inadequate or totally absent vegetation cover over an area. Erosion of the top fertile soil by wind during drought conditions can reach alarming proportions. Dust storms occurring during drought period can remove huge quantities of fertile topsoil. During drought years, both irrigated and dry croplands suffer with the result that there will be extreme production losses in dry areas and considerable losses in irrigated croplands. An analysis of avoidable impacts from future droughts is important for planning for drought.

Drought is a creeping phenomenon. The risk associated with drought is due to the meteorological phenomenon of anomalies in the global circulation pattern and the vulnerability of the region determined by population, landuse, water-use patterns etc. There is very little scope to tame the weather to suit our requirements on a large scale; however, it is inevitable to make adjustment with the weather to extract the maximum benefit from this resource. Thus, planning for drought management and reducing the vulnerability of a region to drought is critical and needs immediate attention.

decision support systems towards forewarning that enables preparedness for various appropriate farming operations.

POLICY ISSUES AND INTERVENTIONS

Policies for development of drought affected regions may be categorized into short / immediate, medium and long-term strategies, which are described hereunder.

Short / Immediate Term

- Need based labour oriented schemes
- Supply of drinking water, feeds / fodder
- Planned mining for drinking water at suitable places
- Effective reserviour management
- Equitable distribution of water for drinking, agriculture, etc.
- Growing short duration naturally drought resistance crops, etc.

Mid Term

- R & D
- Institutional reforms
- Improving infrastructure and market institutions
- Replicating successful watershed projects
- Greater role for states
- Diversification and farming systems approach
- Institutions mechanisms for water harvesting and use
- Artificial recharge of ground water
- Afforestation
- Crop insurance
- Corporatisation
- Indigenous technical knowledge: Encouraging NGO participation
- New Agricultural Policy (NAP)

Long Term

- Creation of surface storage
- Integrating small reservoirs with major reservoirs
- Integrated basin planning
- Inter basin transfer of water
- Increasing water availability in drought prone areas through watershed development

Governmental Efforts

- Crop weather watch groups at nation and state levels
- Food security through buffer stocks
- Prioritization for relief and compensation

CONCLUSIONS

The adverse impact of drought on the ecosystems can be mitigated by understanding the characteristics of drought that enable the selection of appropriate strategies to be implemented at the field level. This calls for an integrated approach considering all the natural resources, including the socio-economic profile of the areas and involving people in the efforts towards combating drought. Remote sensing, GIS and contemporary technologies that have immense potential could be beneficially tapped in this regard.

Characterization of drought

It is important to understand drought characteristics, frequency and severity, and a region's changing vulnerability. Presentation of results of drought climatology in a simple, yet scientific way will help comprehend the drought situations for risk-based drought management.

Almost every year, India experiences drought in some part or the other. Different criteria are followed to identify meteorological drought at different scales of area and time. When the whole country is considered, droughts are classified as severe, if 39.5% to 47.6% of area is affected and as phenomenal, if more than 47.7% of the country is under drought (Kulshrestha, 1997).

Table 1. All India Monsoon Droughts during 1950-2003

Drought category	Calendar year (s)
Moderate	1951, 1966, 1968, 1974, 1982 and1986
Severe	1965, 1979, 2000 and 2001
Phenomenal	1972, 1987 and 2002

It can be seen from the Table 1 that there were 13 droughts of different intensities in India since 1950, in which phenomenal droughts occurred in 1972, 1987 and the latest in 2002. The monsoon drought of 1987 was one of the worst in history with rainfall deficiency exceeding 1.50 SD (Sikka, 1999). India Meteorological Department has officially declared that the year 2002 has been "the first-ever all-India drought year" since 1987. The phenomenal drought situation in 2002 was mainly caused by the dry spell in July, with the rainfall deficiency of 49 per cent during the month being "the worst in the history of recorded observations". Only on two previous occasions in the past (1911 and 1918) did rainfall deficiency exceed 45 per cent in July.

Realistic visualization of drought scenario of India is possible with the knowledge of monsoon rainfall is combined with the spatial distribution of drought-proneness in the country. Considering the Report of the National Commission on Agriculture and additional data from the Central Water Commission of India, Bagchi (1991) has identified 100 districts in India as drought-prone (Table 2).

Table 2. Drought Prone Districts of India as identified by Bagchi (1991)

State	No. of Drought-prone districts	Area affected (%)	Population affected (%)
Andhra Pradesh	8	42	35
Bihar	7	26	22
Gujarat	12	79	68
Haryana	4	33	32
Jammu & Kashmir	2	-	-
Karnataka	14	74	-
Madhya Pradesh	11	-	-
Maharashtra	9	40	36
Orissa	2	15	-
Rajasthan	13	63	45
Tamil Nadu	9	64	-
Uttar Pradesh	6	15	12
West Bengal	3	31	20

Earlier approach for drought management was to wait until an event occurs and try to mitigate its consequences by whatever means available (Ramakrishna et al, 2002). Drought is always managed as a disaster however, knowing that in India, 69 per cent of arable area is rainfed and large number of districts (100) are drought prone, we must adopt a systematic drought management approach for minimizing the impact on livelihoods and natural resources. Integrated watershed management could be the best solution in this direction for combating drought, achieving sustainable agricultural productivity, minimizing land degradation and affecting livelihoods in the region.

It is seen that there is a great year-to-year variation in both the beginning and end of crop-growing season at Kacharam. In the years 1985 and 2000, crop-growing season started as early as end of May. Beginning was most delayed in 1975, when it started in the last week of July. Crop-growing season ended very early by middle of September in 1980, making this year to have shortest growing period of only 14 weeks. Total duration was longest (26 weeks) during 1987 and 1993, in which the season ended as late as third week of December. It is generally observed that variability in the beginning of the season is high compared to the variability in the end. However, no definite relationship between the beginning of season and the total crop-growing period could be observed. Probability for the beginning and end of CGS at Kacharam based on data of 31 years are presented below:

Beginning of CGS at Kacharam	Meteorological week									
	22	23	24	25	26	27	28	29	30	31
Probability (%)	6	23	52	58	71	90	94	94	97	100

End of CGS At Kacharam	Meteorological week									
	41	42	43	44	45	46	47	48	49	50
Probability (%)	94	94	84	81	74	65	42	26	13	6

It can be seen from the above that at Kacharam, there is 50% probability that the crop-growing season begins by the middle of June (24th week) and 70% probability that it begins by the end of June. One can be 90% sure that the CGS begins by 27th week. There is 90% probability that the CGS ends by 42nd week (3rd week of October) and 70% chance that it ends by 2nd week of November (45th week). It is interesting to note that the probability jumps from 70% to 90% in just one week for the beginning of CGS, while it takes three to four weeks to fall from 90% to 70% for the end of CGS.

This indicates a sharp beginning of CGS and the need for critical planning of sowing related operations. During the CGS, if the IMA value falls below 20%, soil moisture availability to crops becomes negligible; if this condition continues for two or more weeks, disastrous drought conditions prevail. It is observed that at Kacharam, such drought conditions occurred in eight years (1971, 1972, 1976, 1985, 1986, 1998, 1999 and 2001) out of the 31-year study period. Classic examples are the years 1972 and 1976 during which the drought occurred in flowering and maturity stages; the year 2001 in which early-season disastrous drought led to total crop loss.

Monitoring of moisture availability to crops at the APRLP-ICRISAT watersheds during the year 2003 was carried out using the water balance technique and the results are presented in Fig. 2. Longest CGS of 26 weeks is observed at Kacharam, however, it suffered from early-season drought of three-week duration. Mentapally experienced shortest CGS of only 14 weeks, but without any disastrous drought spell.

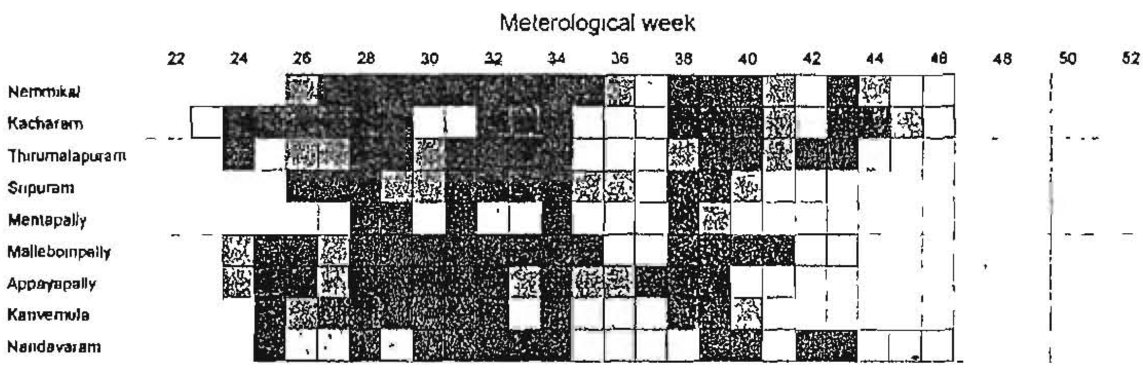


Fig. 2 Drought monitoring at APRLP watersheds during 2003

- Capacity building of local farmers and NGOs for effective dissemination of technologies
- Empowerment of communities, individuals and the strengthening of village institutions
- Initiation of income generating micro-enterprises involving youth, women and landless people
- Continuous monitoring and participatory evaluation by researchers and stakeholders

Combating Drought Impacts through Integrated watershed management practices

The best way to deal with the recurring drought particularly in dryland/rainfed areas is to learn to live with it by minimizing its impacts. Sound agricultural planning/strategies can help in minimizing the drought impacts. Some of the sound integrated watershed management strategies that have developed by ICRISAT in partnership with NARSs by conducting on-station trials and on-farm trials in different watersheds for overcoming hydrological, agricultural and socio-economic droughts are discussed.

Characterization and monitoring of droughts through agroclimatic approach:

Out of these eight districts, under the APRLP-ICRISAT Project, automatic weather stations were installed at the nucleus watersheds during the year 2002 in Nalgonda, Mahabubnagar and Kurnool districts. Weather data is monitored continuously and a database is being developed Long-period rainfall data of the watershed locations is collected and analysed for identifying the beginning and end of rainfed crop-growing season (CGS). Following the methods of Penman and Thornthwaite, weekly potential evapotranspiration and water balances were computed for these watersheds. Based on the Index of Moisture Adequacy (IMA, the ratio of actual evapotranspiration to potential evapotranspiration), the beginning and end of crop-growing season for 31 years (1971-2001) was determined for the Kacharam watershed (Fig.1). Determination of the beginning, end and length of crop-growing season is a pre-requisite for understanding the drought severity conditions in the crop-growing period.

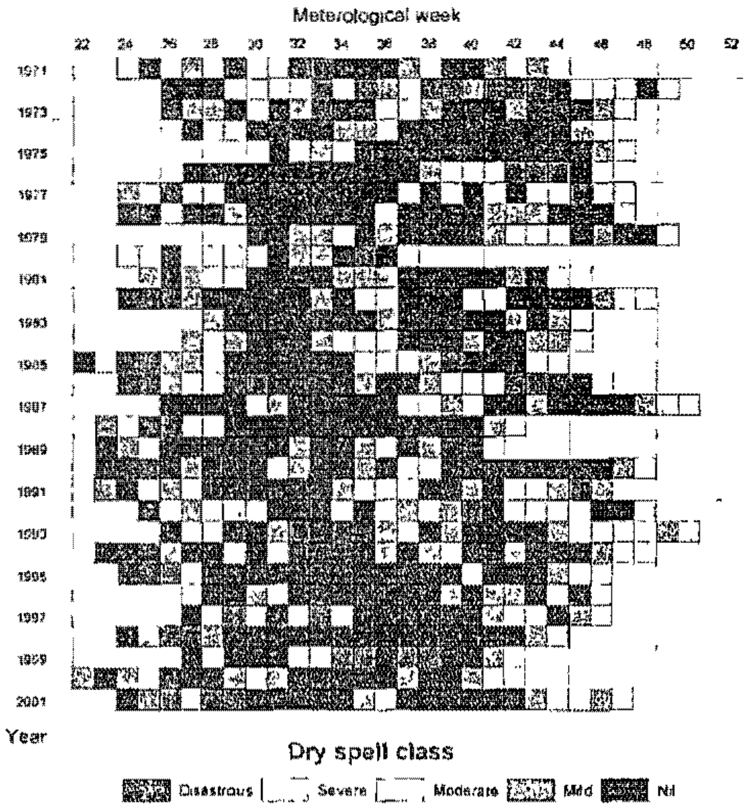


Fig. 1 Length of crop-growing season and drought spells at Kacharam

Table 3. Simulated soybean yields and yield gap for selected locations in India

Location	Mean sowing date	Mean harvest date	Simulated yields (t/ha)		Mean observed yield (t/ha)	Yield gap (t/ha)
			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	0.96	1.01	0.23
Warda	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 Oct	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	-	-

Source: Tsuji et al. 1994

Water and Soil Conservation Measures

In dryland/rainfed areas substantial quantity of soil and water are lost every year thereby leading to poor recharge of the groundwater, productivity and soil health. Soil and water conservation measures taken up at Adarsha watershed like construction of fourteen water storage structures with a capacity of storing 300 to 2000 cu m of water, gully control structures, mini percolation tanks, gabion structure and a 500 m long diversion bund with the active involvement of the local people has resulted in improvement in the water level in the wells particularly in those situated near the check dams (Fig. 3) (Pathak et al (2002).

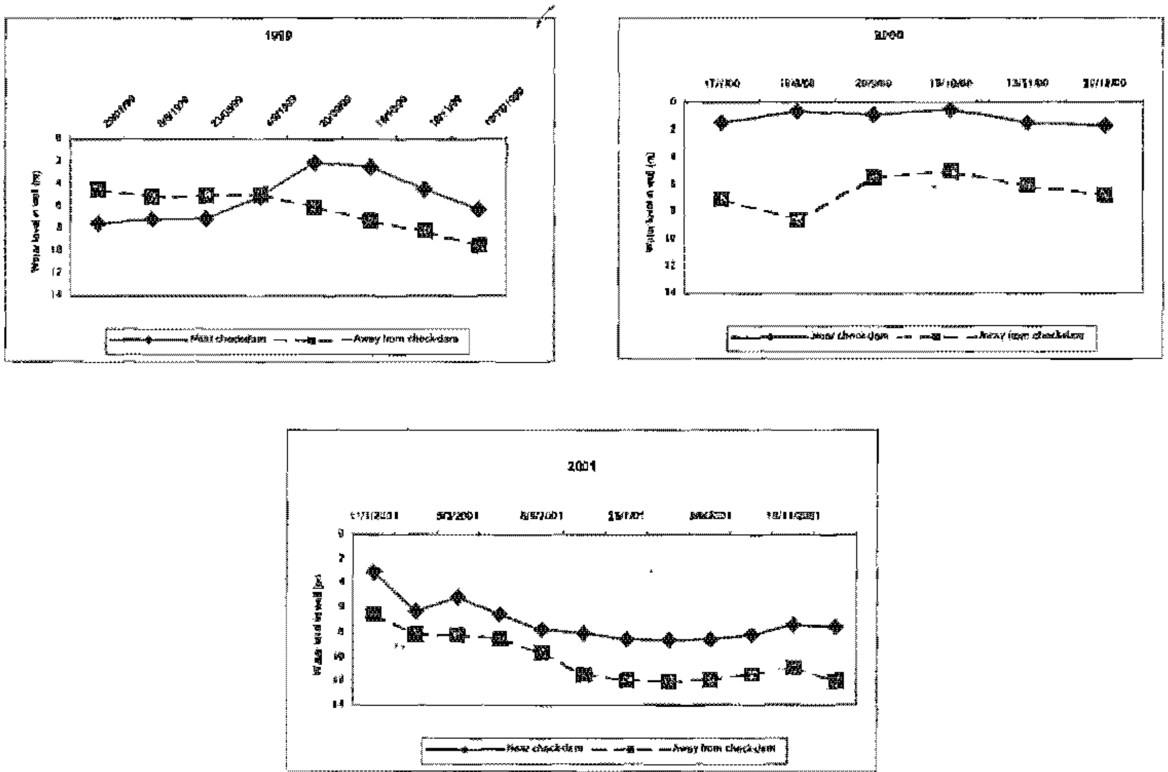


Figure 3 a) Groundwater levels before the construction of check-dam in Adarsha watershed at Kothapally during 1999, b) and c) Effect of check dam on groundwater levels in Adarsha watershed at Kothapally during 2000 and 2001, respectively

Out of all the watersheds, Nemmikal, followed by Malleboinpally and Appayapally, presented the best moisture regime with no drought period. However, the length of CGS differed significantly among these three watersheds with Nemmikal recording the longest (21 weeks) followed by Malleboinpally (20 weeks) and Appayapally (18 weeks). Both Karivemula and Nandavaram watersheds in Kurnool district have experienced disastrous drought conditions in the early-stages and severe drought conditions during flowering phases. Nandavaram experienced rains at a later stage and CGS ended as late as middle of November, while at Karivemula the CGS ended by 1st week of October itself.

The study clearly highlights the usefulness of techniques of water balance for computing the IMA and GIS for determining the CGS and classification of dry spell severity for climatic and drought characterization of watersheds. Near real-time monitoring of moisture availability conditions at the watershed level using these methods can help to better understand the onset of dry spells leading to drought. Proper assessment of these adverse conditions can lead to better drought management advisory to farmers in near real-time for protecting and saving affected crops.

Use of new science tools like simulation models for water budgeting

In drylands/rained areas water is the most important input. Its current use efficiency for crop production ranges between 30-40% and the rest (60-70%) is lost through surface runoff and deep drainage (Wani et al. 2003b). Hence, there is a need to develop strategies to manage this excess water efficiently. Some of the new science tools like simulation models, remote sensing, GIS, etc can help us in devising strategies for efficient management of rainwater. Making use of a simulation model WATBL (Keig and McAlpine, 1974) and weekly rainfall data for the past 30 years, Wani et al (2003b) have worked out various soil-water availability and runoff scenarios for semi-arid India.

The results of their study are depicted in Fig. 3. It can be seen from the figure that in high rainfall (1000-1200 mm) locations like Bhopal, Nagpur, Indore and Adilabad having high water holding capacity (`200 mm) the mean water surplus ranged from 270 to 508 mm. 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 Inceptisol 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 shallow and of lower water holding capacity. This type of water balance studies indicates the opportunities for water harvesting and improved water management so that contingency plan can be prepared for managing the drought.

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

Crop simulation models, using a scenario analysis for the 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 simulated yield was compared with the mean observed yield of the last 5 years to calculate the yield gap. The results (shown in Table 3) 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 gap exists and considerable gains in productivity can be achieved.

Integrated soil fertility management

The yield levels of crops grown in dryland/rained areas are not only low due to erratic nature of the rainfall but also due to poor soil health (deficient in available nitrogen, sulphur, boron and zinc, poor physical properties like water holding capacity, structure, etc). The efficiency of the applied nutrients and utilization of rainwater in dryland/rained areas are also low because of the imbalance use of the nutrients by the resource poor farmers. Improved nutrient management options like application of deficient nutrients, meeting the nutrient requirement of crops through use of organic and inorganic nutrients can help in increasing the utilization efficiency of rainwater and applied nutrients. The results of baseline characterization of soils in the benchmark watersheds at the three districts in A.P. revealed that 81 to 98% of farmers fields were deficient in micro-nutrients such as B, Zn, S along with N and P. On-farm trials conducted in some drought prone watersheds of Mahaboobnagar, Nalagonda and Kurnool districts of A.P. have revealed that application of deficient nutrients like boron, sulphur and zinc resulted in significant increase in yields of maize, greengram, castor and groundnut during kharif 2002 which was a drought year (Table 5)

Table 5. Effect of micronutrients on crop yields in nucleus watersheds, kharif 2002

		Grain yield (kg/ha)		
Watershed name	Crop	Control fields	Micro-nutrient amended fields	Increase over control (%)
Sripuram, Mahaboobnagar	Maize	2630	4560	86
Malleboenpally, Mahaboobnagar	Maize	2980	4570	72
Nemmikal, Nalgonda	Green gram	770	1110	44
Thirumalapuram, Nalgonda	Castor	431	340	49
Karivemula, Kurnool	Groundnut	1430	1825	28

Similarly use of locally available organic manures like farm yard manure, pongamia and neem cake, vermicompost generated through recycling of left-over residues, green leaf manures like *Gliricidia*, etc raised on the field bunds in the watersheds in conjunction with inorganic supplement the nutrient requirement of the crops. Application of these organic manures also result in improvement in soil physical properties like water holding capacity, soil structure and thereby result in increasing the rainwater and nutrient use efficiency.

Integrated Pest and Disease Management

The crops growing in dryland/rained areas not only suffer from deficient soil moisture stress but also from the incidence of pest and diseases due to erratic nature of the rainfall. Management of these pest and diseases through integrated pest and disease management can help in achieving the sustainability of crop production in dryland/rained areas. Some of the interventions evaluated for controlling the pest and diseases in APRLP watersheds were use of pheromone traps to monitor pests, mechanical shaking of pigeonpea to dislodge *Helicoverpa* larvae, use of neem seed kernel extract for insect control, use of tolerant cultivars, use of *Helicoverpa* nuclear polyhedrsis virus, seed treatment etc.

Income generating activities

The first and the most severely affected section of the society due to drought is the poor and landless because of the increased unemployment due to failure of the rains. Any programme that aims in combating or minimising the drought impacts should aim in developing means and ways for earning their livelihoods by providing alternate income generating activities. In integrated watershed management programme this issue has been duly addressed by promoting the micro-enterprise activities like vermicomposting, establishment of village-based seed banks and value addition of pigeon pea.

Environmental Services

Carbon sequestration refers to the storage of carbon in stable form either by direct or indirect fixation of carbon-dioxide. Based on the long-term experiments (1977-2002) conducted on Vertisol watersheds, Wani et al (2003a) have reported about 335 kg C/ha/year

The water level in these wells was consistently higher (around <3m) even during below normal rainy season, whereas the water level in wells located away from the check-dams was about 6 m deep. Due to increased water availability, a total of 200 ha in post *kharif* and 100 ha in post *rabi* season was brought under cultivation. These soil and water conservation measures also resulted in reduction of soil and runoff loss. Similarly at Lalatora watershed, Vidisha district, Madhya Pradesh the water level in open wells was about 6.5-9.5 m before the implementation of the watershed activities ie 1998-99. After the implementation of the integrated watershed activities the water level increased substantially. During 2000, the mean water level in the wells near the check dams was consistently around 1.5 to 2 m up to October whereas water level in the wells located away (about 1000 m) from the check-dams was about 8.5 m throughout the year (Pathak et al 2002).

Crop diversification

Crop diversification is another component of integrated watershed management for achieving increased and sustainable production in dryland/rainfed areas. Some crops have the ability to withstand water stress conditions, whereas some do not possess this character. This difference in the response of various crops to a given environment is used to minimize the drought impacts. One good example of crop diversification that has helped in achieving higher yields even during the deficient rainfall years is the intercropping or mixed cropping. Trials conducted in Adarsha watershed have revealed that maize plus pigeon pea in the ratio of 2:1 was found to be the best intercropping system as compared to sole maize or sole pigeon pea. Appropriate cropping sequence/rotation suiting to the rainfall and soil properties of a water shed can also help in minimizing the drought impacts. It can be seen from the data presented in Table 4 that of the different cropping systems tried at Adarsha watershed, maize/pigeon pea and maize followed by chickpea proved to be the most beneficial as these crops could utilize the available soil moisture stored in different horizons more efficiently (Wani et al 2003c).

Introduction of new crops having low water requirement, high biomass production and which can fetch high returns to the farmers can also help in sustaining the production and improving the livelihoods of the farmers in drought prone areas. Efforts are underway to introduce some medicinal and aromatic plants like *Cymbopogan flexuosus* (lemon grass), *Vetiveria zizanoides* (vettiver), etc in-lieu of paddy in some watersheds of Kurnool, Nalgonda and Mahaboobnagar districts. The water requirement of the lemon grass, etc is only one-third of paddy and groundnut whereas the profit is more than 2-fold. Introduction of these aromatic and medicinal plants will help not only in getting higher profits but the water saved can also be used for drinking, cattle rearing and other for purposes.

Table 4. Total productivity, cost of cultivation, and income for different crops at Adarsha watershed during 1999–2000

Cropping system	Total productivity (kg ha^{-1})	Cost of production (Rs ha^{-1})	Total income (Rs ha^{-1})	Profit (Rs ha^{-1})	Benefit-cost ratio
Maize/pigeon pea (improved)	3351	6203	22709	16506	2.67
Sorghum/pigeon pea (improved)	2285	5953	17384	11431	1.92
Cotton (traditional)	980	15873	24389	8516	0.54
Sorghum/pigeon pea (Traditional)	1139	4608	11137	6529	1.42
Maize/chickpea (Improved)	4319	7317	26774	19457	2.66
Chickpea (Improved)	840	4886	17292	12406	2.54
Sole maize (Improved)	3150	4578	13532	8954	1.96
Sorghum (Traditional)	975	3385	6997	3612	1.07
Sole sorghum (Improved)	2800	4352	15084	10732	2.47
Maize (Traditional)	1600	3599	7281	3682	1.02
Greengram (Traditional)	600	4700	9000	4300	0.91
Chickpea (Traditional)	-	4260	11600	7340	1.72
Sole pigeon pea (Improved)	1090	4890	17120	12230	1.35

can be sequestered by employing integrated watershed management practices along with pigeon pea - based systems. Conservation of this carbon in soils helps in building up the soil organic matter, improving the soil physical properties like structure, water holding capacity, aggregate stability etc and also reduce the level of green house gases in the atmosphere. In the community watersheds through SWNM options, degraded lands are being rehabilitated using forage grasses and biodiesel plantations using *Pongamia pinnata* and *Jatropha caracus*. These plants also help in saving C emissions to the environment through C switch from fossil fuel to vegetable oil and also sequester C in soil (D'silva et al., 2004).

References

Bagchi, K.S. 1991. Drought Prone India – Problem and Perspectives. Vol. I & II, Agricole Publishing Academy, New Delhi

Emmanuel D'Silva, Suhas P. Wani and Basre Nagnath. 2004. The Making of a New Powerguda Community Empowerment and New Technologies Transform a Problem Village in Andhra Pradesh. In Press.

Keig, G. and McAlpine, J. R. (1974) WATBAL: a computer system for the estimation and analysis of soil moisture regimes from simple data, 2nd Technical Memorandum, 74/7, Australian Division of Land Research, CSIRO, Canberra

Kulshrestha, S.M. 1997. Drought Management in India and Potential Contribution of ClimatePrediction. Joint COLA/CARE Technical Report No.1.

Pathak, P., Wani, S.P., Piara Singh, Sudi, R. and Srinivasa Rao, Ch. (2002) Hydrological characterization of bench mark agricultural watersheds in India, Thailand , Vietanam, Global Theme 3, Report no.2. Patancheru 502 324, Andhra Pradesh, India: International Crop Research Institute for the Semi-Arid Tropics.52p

Ramakrishna, Y.S., Sharma, K.D., Rao, G.G.S.N. and Kesava Rao, A.V.R. 2002. Climatalogical Aspects of Droughts and their Management. Proc. Recent Trends in Drought Assessment, Monitoring and Management, CSRE, IIT, Bombay. Pp.8-15.

Sikka, D.R. 1999. Monsoon drought in India. Joint COLA/CARE Technical Report No.2.

Tsuji, G.Y., Jones, J. W., and Balas, S. (eds)(1994) DSSAT v.3 University of Hawaii, Honolulu, Hawaii.

Wani, S.P., Rego, T.J. and Pathak, P (eds) (2002) Improving management of natural resources for sustainable rained agriculture. Proceedings of the training workshop on On-farm Participatory Research Methodology. 26-31 July 2001, Khon Kaen, Bangkok, Thailand, ICRISAT, Patancheru, Andhra Pradesh, India pp.68

Wani, S.P., Pathak., P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003a). Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. Soil Use and Management (2003) 19, 217-222.

Wani, S.P., Pathak, P., Sreedevi, T. K., Singh, H.P and Singh, P (2003b) Efficient management of rainwater for increased productivity and groundwater recharge in Asia. In Water Productivity in Agriculuture: limits and Opportunities for Improvement (eds J. W.Kijne, R Barker and D Molden) CAB International. 2003

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.j., Shiferaw, B. and Iyer, S.R. (2003c) Farmer-participatory integrated watershed management:Adarsha watershed, Kothapally India. An innovative and upscalable approach. In Research Towards Integrated Natural Resources Management (eds .R. R. Harwood and A. H. Kassam) Interim Sciene Council, Centre Directors Committee on Integrated Natural Resources Management, Rome 2003.