WATER HARVESTING IN ARID TROPICS

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Preface

Water is a severe constraint in the arid tropic. Therefore, research priorities were given to the optimum use of rainwater, groundwater, conjuctive use of rainwater and groundwater to the modern and sophisticated system of drip irrigation that squeezes every drop of the limited water resources, and to cropping patterns that complete life cycles during the rainy season. Researches on these thrust areas were initiated simultancously in the late sixties.

Aspects other than efficient use of rainwater have been published in various national and international journals. Six pieces of manuscripts on the optimum use of rainwater had been contributed to the Agronomy Journal of the American Society of Agronomy.

However, the paper had to be withdrawn from that prestigious journal at the very last moment due to certain unavoidable circumstances. Subsequently, it was decided to publish the material in the CAZRI publication series. The papers are being presented here in the same style as set by the Style Manual of the Agronomy Journal.

As important as these scientific aspects, are the words of acknowledgement with which I shall conclude this preface. Grateful acknowledgements are made to Dr. H.S. Mann and K.A. Shankarnarayan, former Directors, CAZRI, for research facilities, to Dr. P.K. Ghosh, Chairman, Publication Committee for judging the manuscripts regarding their suitability for publication, and to Mr. Murlidhar Sharma for typing the manuscripts.

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Using Pond Sediment Treated Catchment

S.D. Singh

ABSTRACTS

The paper deals with hydrological characteristics of pond sediment treated water harvesting catchment constructed in the cultivated field at a typical site in the Indian side of the Thar desert. Based on 75 years of rainfall records during growing season (July-Sep.), expected daily rainfall extreme in a week averaged 85, 44, and 22 mm at the 5, 20, and 50% frequencies of occurrence, which were found to predictively yield 53, 26, and 12 mm of runoff, respectively. Predicted runoffs were similar to measured ones. For instance, 25.5 mm of runoff from 45.7 mm of shower and 12 mm of runoff from 22 mm of shower were observed. The relationship between rainfall intensity, duration, and frequency showed that at the 80% probability the maximum rainfall intensity was 22 mm/h for the 5 min duration and 17 mm/h as the time interval increased to 10 min. Rainfall intensity pattern was such that 75% of showers occurred as showers of advanced type, whereas 25% of them occurred as showers of delayed type. From 0.5 catchment to crop area ratio, each ha of crop area received 140-636 mm of rainwater, although the rainfall recorded was 117-528 mm in different years Average runoff efficiency was 66%, with threshold retention of 4.5 mm. The first year, runoff efficiency was 84%. It decreased to 56% by year 2. After this year it resumed the phase of an increase reaching 76% by year 6. Rising efficiency could be attribuied to natural sealing of treated surfaces by green algal growth.

INTRODUCTION

In arid regions water is inadequate to support sound agriculture. Many arid areas can improve their agricultural water supply by means of water harvesting. It is practised in a variety of ways (Cooley *et al.*, 197:). Roaded catchments, most widely used for developing arid rangelands in Western Australia (Carder, 1970) are well suited for undulating ground surfaces that contain a clay layer within 1 m of the surface (Dedrick, 1975). Runoff collecting conduits to harvest water from hillside catchments and use of harvested water for cultivation on terraced valley fields and valley bottom land have been used in the Negev highland desert of Israel (Evenari *et al.*, 1968). Use of this method is limited to hilly tracts.

Researches on the water harvesting methods carried out in the United States include installations of level bench terraces in the Great Plains and compacted earth catchment as well as desert strip farming in Arizona. The level bench terraces were not found very successful due to water logging for quite sometime, even though the installation had shown considerable moisture conservation and increased crop yields in isolated experiments of Mickelson (1962), Houser and Cox (1962), Buchta *et al.* (1965), and Phillips (1965). Compacted earth catchment yielded only 35% runoff (Cluff, 1975). whereas added expense on fencing to rainfall collector area (Morin and Matlock, 1975) to allow grazing jeopardises adoption prospects among farmers of low economic group in the third world countries.

Numerous catchment construction materials have been used for increasing the runoff. A silicon catchment on a loamy sand soil in Arizona produced 90% runoff during the first year, but runoff gradually decreased to 50% after five years (Fink and Frasier, 1977), whereas a paraffin wax treatment on a sandy loam soil produced 90% runoff for over two years with no usual signs of deterioration, but the effectiveness varied according to site, soil, and climate (Cooley *et al.*, 1975). Materials like butyl rubber, plastic, and sheet metal produce 100% runoff (Cooley *et el.*, 1976) but are very expensive.

This paper deals with a method of water harvesting which consists of applying indigenous available pond sediments on compacted earth catchment on a loamy sand soil in the cultivated field. Motivation for this experiment came from an observation in the 1968 dry season in which, while all crops failed, pearl millet and grain legumes thrived well in ribbon-like depressions located adjacent to runoff contributing farm roads. Similar observations were made in 1969, one of the driest seasons in living memory of the Thar desert.

MATERIAL AND METHODS

A field study on a compacted earth catchment treated with pond sediments was conducted in the rainy season (July through September) from 1972 through 1975 at Jodhpur. The soil was coarse loamy Typic Camborthid with sand, silt, and clay content at 85.2, 4.8, and 9.9%, respectively.

The climate of Jodhpur (26° NL, 73° EL, 254 m above MSL) is arid. The 80-year normal average annual rainfall is 361.2 mm, 83% of which being concentrated in the rainy season. Temperatures are high in summer-Apr.-June, May being the hottest month with mean maximum temperature of 41.6°C. Winter-Nov.-Mar. is rainless, calm and mild, with Jan. being the coldest month. Relative humidity averages 45% in winter, 15 to 17% in summer, and 60 to 80% in rainy season. Mean wind speed is more than 10 km/h from Apr. to June. Atmosphere remains calm during the rainy and winter seasons. Sunshine is abundant. Reference crop evapotranspiration, computed by the modified Penman's method, is 8.3, 6.7, and 6.7 mm/d in July, August, and September, respectively.

The treatments included four catchment to cultivated area ratios (Fig. 1) as noted below :

$\frac{Am}{Ac}$ = 0, 3 m wide level plot of 30 m length without catchment as flat surface control.

$\frac{Am}{Ac}$ = 0.50, 3m wide level plot below the 1.5 m wide catchment 30 m long.

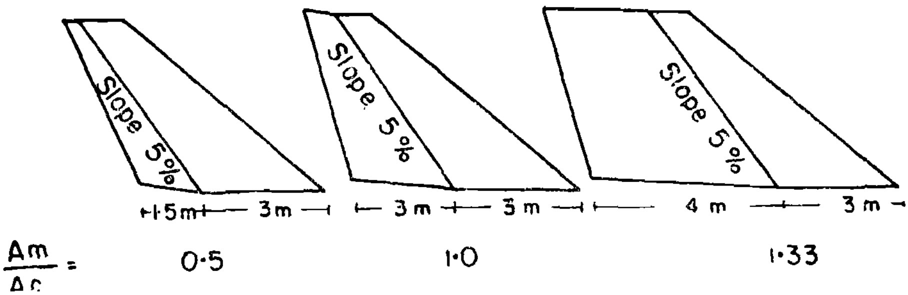

Fig. 1. Layout plan of microcatchment farming.

$\frac{Am}{Ac} = 1.00$, 3 m wide level plot below the 3 m wide catchment 30 m long.

$\frac{Am}{Ac} = 1.33$, 3 m wide level plot below the 4 m wide catchment 30 m long.

Am = catchment area.

Ac = cultivated area, dictated by cultural ease and economy, chosen in 3 m width in which tillage and planting operations were manageable by machines.

The catchment was prepared, in a uniform cultivated field, by shaping the soil surface with utility blade attached to a tractor, followed by smoothing and compacting the surface by ramming and rolling. After applying 5 mm thick layer of pond sediment, which was 57% sand, 15% silt, and 16% clay, and wetting the surface was further compacted with a heavy roller. A 5% slope was provided to facilitate diversion of runoff to cultivated area.

Date, depth, and intensity of rainfall were recorded by a recording type of rain gauge installed at the site. Cumulative runoff produced by each runoff-producing storm was measured on runoff plots marked as portions of catchment (1.5 m x 2 m in $\frac{Am}{Ac} = 0.50$, 1 m x 3m in $\frac{Am}{Ac} = 1.00$, and 0.75 m x 4 m in $\frac{Am}{Ac} = 1.33$). Smooth aluminium sheet of 15 cm width was fixed on all the four sides of runoff plot to mark impermeabilised boundary. On the lower side of the catchment aluminium guttering from the plot led to a water collection drum. The drum was covered with a lid to avoid rain entry. Water level rise in the drum was measured by the dip-stick. The dip-stick values were converted into volume of runoff. The volume of runoff divided by the area of runoff plot gave millimetres of runoff. Precipitation minus this runoff gave the quantity of water retained on catchment and negligibly lost in interception and evaporation. Total depth of water received by cropped area below each catchment was computed using the identity :

$$D = P + Q\frac{Am}{Ac} \qquad (1)$$

Where,

D = depth of water in millimetre

P = precipitation in millimetre

Q = runoff in millimetre

Am and Ac are as before.

The crop cultivation terminated in 1975, but rainfall and runoff measurements were continued until 1977.

RESULTS AND DISCUSSION

Rainfall Frequency, and Storm Intensity, Duration, and Pattern

To evaluate whether sufficient rainfall occurs during the period favourable for crop growth, and whether sufficient runoff can be obtained to maintain plant growth, a frequency distribution analysis of 75 years of rainfall at Jodhpur was carried out following the log normal distribution. Storms below 2.5 mm, which are likely to be ineffective and those of very low frequency which can cause floods, were not considered.

Estimated daily rainfall extremes in a week period are given in Table 1 for the low, intermediate, and high frequencies of occurrence. In the 75-day growing period from the first week of July to second week of September, in which early maturing crop varieties adapted to this region complete their life cycle, expected daily rainfall extreme in a week averaged 85 mm at the low-frequency of occurrence, 22 to 44 mm at the intermediate frequencies, and 10 mm at the high-frequency of occurrence. In the later half of September when monsoon will be receding, daily rainfall maximum is expected to be 3 and 13 mm at high and low probabilities of occurrence, respectively.

Table 1. Probability of occurrence of rainfall in the growing season (July to September) based on 75 years of rainfall at Jodhpur

Month	Week	Rainfall equal to or more than amount (mm) indicated at various probabilities			
		Low frequency	Intermediate frequency		High frequency
		5%	20%	50%	80%
	1	85	43	21	10
July	2	72	37	19	9
	3	87	43	21	10
	4	83	41	18	6
	1	89	47	24	12
August	2	103	51	25	12
	3	69	35	18	9
	4	105	54	27	14
	1	64	36	19	10
September	2	99	48	23	11
	3	11	7	5	3
	4	15	9	5	3

Fig. 2 reproduces the daily rainfall charts showing date, time, and amount of daily rainfall and rainfall intensity pattern recorded in the four years. From the analysis of rainfall charts for the 5, 15, 30, and 60 min time intervals, Fig. 3 was constructed to generate the relationship between rainfall intensity, duration, and frequency and to determine from these curves the likely intensity of a storm at given probability. At the 80% probability the maximum rainfall intensity was found to be 22 mm/h for the 5 min duration. It decreased to 17 mm/h as the time interval increased to 10 min, exemplifying a general trend for the rainfall intensity to decline as the rainfall duration increased.

Rainfall intensity pattern is basic to yield of runoff. As shown in Fig. 2, 75% of showers occurred as showers of advanced type, whereas 25% of them occurred as showers of delayed type. To induce runoff peaks from advanced storm pattern which brings about high intensity when infiltration on catchment may be high, it is necessary to treat the catchment with low-cost easily available material.

Runoff Frequency

To evaluate runoff prospects the frequency distribution of precipitation as well as the runoff efficiency predicted from the rainfall to runoff relationship were used.

In large part of the growing season, the low frequency daily maximum rain in a week averaged 85 mm, which would predictively yield 53 mm of runoff. The available water supply (rain + runoff) to the crop area would satisfy, or exceed the water storage capacity of the 90 cm profile. A rainfall of 44 mm expected at the 20% probability would produce runoff as high as 26 mm, which was similar to an observed runoff of 25.5 mm from a 45.7 mm shower. This runoff plus rain may suffice the crop water requirements (6.7 ha-mm) for a period of 10-12 days. The runoff from 22 mm of rainfall expected at the 50% probability was 12 mm, whereas in one instance the measured runoff was 12.8 mm from a shower of 22.1 mm.

In the third and fourth weeks of September when monsoon approaches the fag end, rains at the 50 and 80% probabilities can never produce runoff, since the storm sizes are not more than "threshold rain". Rainfalls at the 5 and 20% probabilities can produce 4 to 6 mm of runoff provided the intensity is about 22 mm/h. An observed storm size of 11.2 mm which occurred at the rate of 22.8 mm/h had produced 4.4 mm of runoff.

For the growing season July to September, the 80-year mean rainfall has been at 298 mm, the potential crop evapotranspiration at 666 mm; thus the 368 mm may be the expected water deficit crops may experience in the growing season. Adding runoff to rainfall, pond sediment treated compacted earth catchment considerably increased the depth of water available for crop use (Table 2). From catchment to cultivated area ratio of 0.5, each ha of cultivated area received 450 to 2150 m^3 of runoff water (1 mm equals 10 m^3 of water per ha) from the catchment in addition to 1170 to 5280 m^3 from direct rain. The cultivated area then received 1400 to 6360 m^3 of water which is

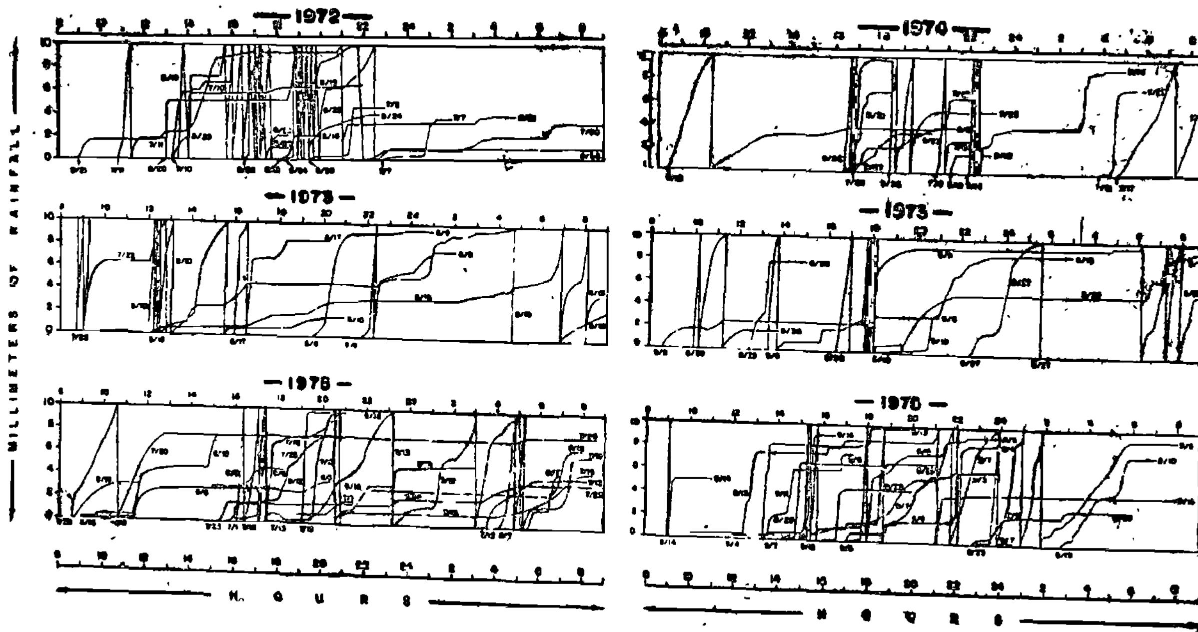

Fig. 2. Date, time, and amount of daily rainfall and rainfall intensity pattern recorded at Jodhpur from July to September.

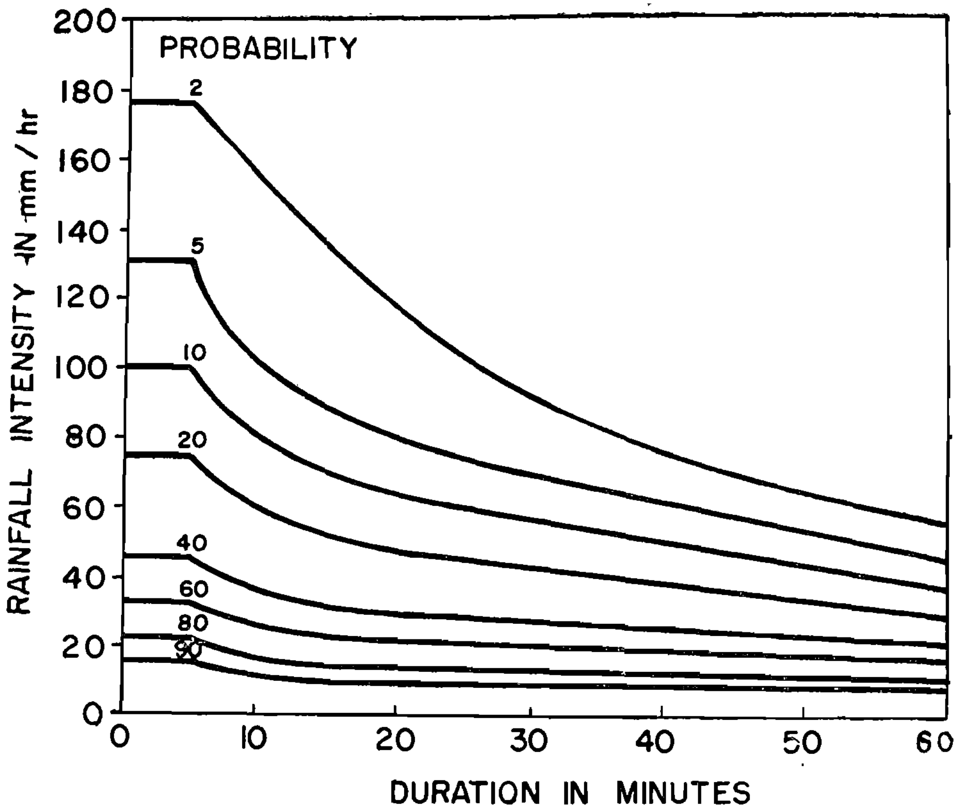

Fig. 3. Rainfall intensity-duration curves for several probability levels.

equivalent of some 140-636 mm of rainfall, although the rainfall was 117-528 mm in different years. Obviously, the catchment redistributed rainfall over crop area where the water was concentrated and must have moved deep in the soil, safe from evaporation. Fairbourn and Gardner (1974) found that micro-watershed and vertical mulching allowed infiltration of harvested water deep in the soil thereby saving 41% of soil moisture.

Table 2. Growing season rainfall (P), runoff (Q), and depth of water (D) in crop area

Year	P	Q	D			
			0.0	0.5	1.0	1.33
	mm					
1972	306°	208	306	410	514	583
1973	528	215	528	636	743	814
1974	117	45	117	140	162	177
1975	290	126	290	353	416	458

°282.4 mm occurred from daily rainfall during 15 to 25 August

Rainfall-Runoff Relationship

Relation between rainfall and runoff was needed for extrapolation or interpolation of runoff from the 80 years of rainfall records.

The best line of the form

$$Q = a + bP \qquad (2)$$

Where,

Q = runoff in millimetre

a = intercept of best fit line

b = slope of best fit line

P = rainfall in millimetre

was computed from the daily rainfall and runoff data recorded over four years. The computed line of the best fit was

$$Q = 0.66\ P - 2.95 \qquad (3)$$

Regression coefficient was significant at the 0.001 level of probability, and rainfall alone accounted for 90% ($r^2 = 0.90$) of the variability in runoff. For the runoff, Q, set equal to zero in equation (2),

$$P = -\frac{a}{b} \qquad (4)$$

The value of P in equation (4) is the minimum, or threshold, quantity of rainfall necessary before runoff occurs, and "b" represents the runoff efficiency after the "threshold rain" has been exceeded. The relationship in equation (3) showed the threshold rainfall was 4.5 mm, and runoff efficiency was 66%, which are close to threshold value (4.6 mm) and runoff efficiency (62%) in studies by Frasier (1975) in Arizona.

For the growing season 1972 through 1975, total rainfall averaged 378 mm from an average of 24 separate rainfall events per season. During this period, 25% of rainfall events occurred as showers more than the quantity necessary before runoff occurs but storm intensity was too low to produce runoff. These separate showers represented 56 mm of potential runoff. Another 25% of showers occurred as showers less than threshold rain, representing 13 mm of potential runoff. For the remaining 12 showers, 54 mm of potential runoff would be lost, for a total of 123 mm or one-third of the average seasonal rainfall.

Relationship between Runoff and Storm Intensity, Storm Duration and Peak Intensity Duration

The multiple regression model

$$Q = a + b_1 I + b_2 T + b_3 D \qquad (5)$$

Where,

Q = measured runoff in millimetre

a and bs = constants in the regression line

I = average of all 5 min time interval intensities found to be equal to or more than the maximum rainfall intensity of 22mm/h predicted from Fig. 3 for the 80% probability for the 5 min duration. Hereinafter referred to as "peak intensity duration"

T = cumulative time in minutes a given storm occurred at intensity I

D = storm duration in minutes,

was computed from data obtained from the daily rainfall charts of rain recorder.

In the fitted regression model (Eq.6)

$$Q = 0.24\ I + 0.69\ T + 0.03\ D14.7 \qquad (6)$$

the coefficients emerged significant at the 0.001 level of probability, and the 88% of variations in runoff was accounted for by independent variables as described above.

Among variables included in the analyses, storm intensity contributed substantially to runoff but relative contribution of peak intensity duration was the highest at 70%, whilst that of storm duration was least. That peak intensity duration plays important role to yield of runoff was further borne out from zero runoffs obtained from certain storms occurring at intensities ranging from 30 to 59 mm/h but lasting only for a 5 min duration.

Treatment Efficiency and Durability

Rainfall-runoff relationships as expressed in equations (2) and (4) were used to obtain yearly (i) threshold values and (ii) efficiency of runoff, which are reported (Fink and Frasier, 1977) to provide useful information about treatment efficiency and durability. For a silicon-treated catchment, the threshold retention Po was found to be small (Po = 0.39 mm) and runoff efficiency was 100% (b=1.00) in the first year of treatment (Fink ann Frasier, 1977), but as the treatment weathered the threshold retention tended to increase, runoff efficiency steadily decreased to as low as 50% after five years of treatment.

Our Fig. 4 depicts threshold values and runoff efficiency for a pond sediment treated catchment that would never have 100% runoff.This figure shows the overall pattern did not resemble the threshold retention and runoff efficiency patterns reported earlier for a silicon catchment. The first year, runoff efficiency was 84%

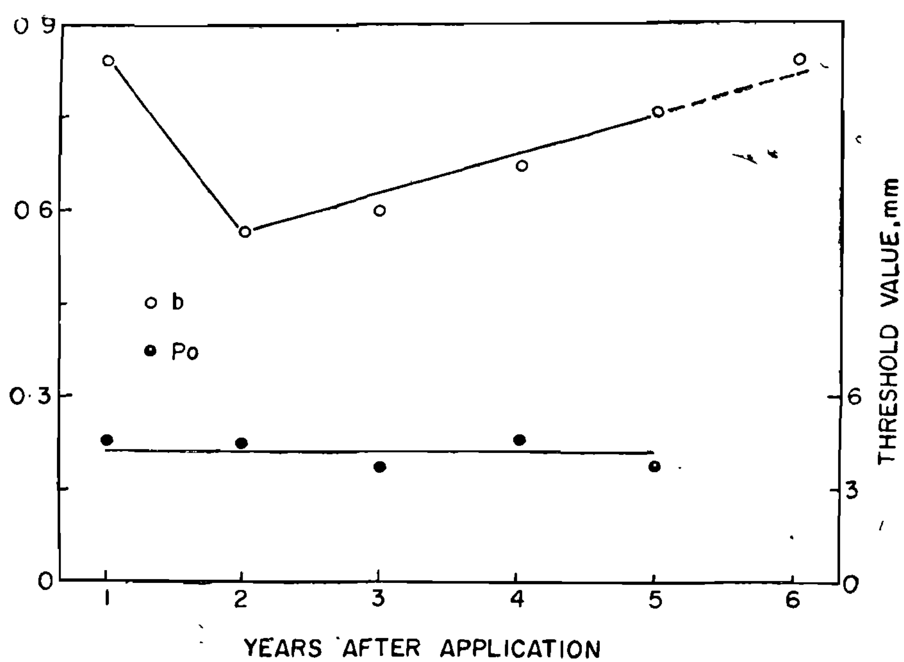

Fig. 4. Yearly threshold values and runoff efficiency for a compacted earth catchment treated with pond sediments. In 1974 the number of storms producing runoff was too small for valid statistical analysis.

(b = 0.84) after threshold retention of 4.5 mm (Po=4.5 mm); and the coefficient of determination approaching unity (r^2 =0.99)which is typical for highly efficient water harvesting catchment. Unlike silicon catchment, threshold retention was found to be similar across the years, thereby indicating that catchment surfaces were close to smoothness at installation, and loss of precipitation in wetting of treated surfaces was similar over five years following the treatment.

By year 2, the runoff efficiency decreased to 56% (b = 0.56) and 44% of rainfall was infiltrating the soil as the wetting front advanced through the treated zone. Following year 2, it resumed the phase of an increase approaching a value as high as 76% (b = 0.76) by year 6. Rising efficiency, unlike that for a water-repellant catchment, could be attributed to the natural sealing of treated surfaces by green algal growth over years following the treatment. Natural sealing due to algal growth with rains has been able to maintain until year 1983 the treated surfaces as smooth as were built initialy. The only maintenance operation needed was control of a few scattered annual weeds emerging with the first rain by single spray of a 0.1% gramoxone solution.

In studies of Fink and Frasier (1977) on a silicon catchment, the runoff efficiency was found to be 76% by year 4 after the first treatment, same efficiency was found once again by year 3 after the first re-treatment, and a 68% efficiency after the second re-treatment in year 11. The 68% runoff efficiency was achievable following three silicon applications in a span of 11 years. On the other hand in my studies, after losing efficiency the pond sediment catchment self-restored 67% runoff efficiency by year 5, 76% by year 6, and would presumably restore the original 84% efficiency by year 7 (obtained by extrapolation). It is not intended here to say that the efficiency would exceed 84%, since pond sediment is a material that cannot have 100% runoff, like the materials such as butyl, plastic or sheet metal.

Silicon and similar chemical materials are expensive, whereas three applications over a span of just 11 years to maintain satisfactory water repellancy, further enhance the construction outlay, as compared to indigenously available high-efficiency compacted earth catchment over a limited area at the potential site (s) in a region.

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Runoff Utilization For Increasing Crop Yields

S.D. Singh

ABSTRACT

Response of pearl millet [*Pennisetum americanum* (L.) Leeke] to water harvesting system with four catchment to crop area ratios namely 0.0 (flat surface control), 0.5, 1.0, and 1.33 was studied on a loamy sand soil in the Thar desert, India. Crop water supply, over the check, ranged from 23 to 60 mm in the extremely dry season and 108 to 286 mm in the season with a good rainfall. As a result, in water harvesting plot with 0.5 ratio, a yield of 3717 kg/ha was obtained in the 1971 season with 69% of normal rainfall. This yield was comparable to maximum yield of 3590 kg/ha recorded in a recent study on the same cultivar of pearl millet subjected to water supply and management practices least limiting to yield. This ratio (0.5) was found optimum for the type of soil, climate, and surface sealing pond sediment. In water harvesting plot having this ratio, crop water supply at 350 mm in the season with medium rainfall appeared to be desirable. Because at this level 85 kg of grain for each 10 mm of water supply and a yield of 2900 kg/ha could be anticipated. Further, it was observed that threshold requirement was the major part of the crop water requirement at the low yield level in the low rainfall season.

INTRODUCTION

The minimum rainfall for producing a crop in dry farming areas with summer rainfall pattern is estimated as 500 mm (Koeppe and Long, 1958). At a typical site in Indian part of the Thar desert the growing season (July-Sept.) normal average rainfall during the 80-year period of record is 298 mm. Therefore the rainfall is not sufficient to ensure a good crop.

In conditions of dryland farming, the solution to soil moisture problem lies in the storage of rainfall in the potential root zone of the soil either by means of suitable fallows (Mathews, 1951; Evans, 1957; Russell, 1961), or by the water harvesting methods. Data from studies conducted in the Great Plains from Texas to Canada indicate that the amount of water remaining in the soil after a fallow period may be only 15-30% of the total precipitation received during the period (Jensen, 1968). Efficiency of fallow is expected to be negligible in this area, because xerophytic weeds that grow profusely on drylands during nine months dry period from Oct. until June would utilize the water stored by fallowing. Water harvesting therefore appears to be an alternative to fallowing for increasing the available water supply for plant growth.

Level bench terrace system originally developed by Zingg and Hauser (1959), has received considerable attention in the late sixties (Cox, 1968; Hauser, 1968; Mickelson, 1968) and early seventies (Haas and Willis, 1971; Viets, 1971). Excess supply of water and need for diversion of runoff when rainfall events are closely spaced have been a few of the problems of this system.

In dry farming areas where land is plentiful and water scarce, crop failure is a recurring feature. Water harvesting system that uses a portion of the land as catchment to harvest runoff and divert it to adjacent crop area has proved beneficial. Myers (1967) has developed a similar system but his method provides water for livestock, and as such has limited experimental use on crop lands. Fairbourn and Gardner (1974) have recommended ridge furrow system with a contributing slope to crop area ratio of 3 to 1 for producing of grain sorghum [*Sorghum bicolor* (L.) Moench.] on a silt loam soil in the semiarid Great Plains. In a 30 cm winter rainfall area, Luebs and Laag (1974) found a significant increase in grain yield of barley (*Hordeum vulgare* L.) in only one of three years. Results may be quite different in a summer rainfall area, since rainwater use efficiency, same as anticipated in a winter rainfall area, cannot be achieved.

The objectives of this study were to evaluate several catchment to crop area ratios and study the effectiveness of water harvesting for increasing and stabilizing the yields of pearl millet (*Pennisetum Americanum* (L.) Leeke) on a loamy sand soil in a summer rainfall area of the Thar desert. Determined from the 80-year rainfall record at Jodhpur, expected number of spells in the growing season was 14, five of them with intensity more than 25 mm/h. and two of them with intensity more than 50 mm/h, showing that the frequency and amount of rainfall were quite favourable for obtaining sufficient runoff and utilizing limited quantities of rainfall.

MATERIAL AND METHODS

The research site, soil and climatic characteristics, treatments employed, recording of daily precipitation and runoff, construction of catchment, and surface sealing material used have been described in first chapter of this series of papers.

The treatments comprising four catchment to crop area ratios namely 0.0, 0.5, 1.0, and 1.33, allowing 100, 67, 50, and 43% of the given total area under cultivation, respectively, were arranged in a randomized block design with six replications. Hybrid pearl millet [*Pennisetum americanum* (L.) Leeke] cv BJ 104 one of the few well-adapted dryland crops, was selected as a test crop. A mixture of urea and diammonium phosphate was applied to supply 80 and 26 kg/ha of N and P, respectively. One-half of N and full dose of P were applied at the time of planting, whilst remaining one-half of N was top dressed with rain about a month after planting. The cultivated area adjacent to catchment area was planted by a seed drill unit with six rows of seeding attachment 50 cm apart, on 10 July 1970, 1 July 1971, 12 July 1972, 9 July 1973, 19 July 1974, and 1 July 1975.

Plants within a row were thinned to 15 cm. Crop was harvested 75 days after planting.

Gravimetric determination of soil moisture content before, after, and between rains was done from samples taken at the 30 cm interval to the 90 cm profile. Soil water in residual storage at time of harvest and loss of water as deep percolation were determined by the field moisture balance method.

The grain yields, crop water supply in the growing season, and water use efficiency were analysed to evaluate the effectiveness of the given treatments.

RESULTS AND DISCUSSION

Growing Season Rainfall

Data on rainfall, beginning the first week of July and ending 30 Sept., and runoff measured from the pond sediment catchment at the test site are summarized in Table 3. The 6-year average rainfall was 358 mm, whilst the 4-season runoff averaged 170 mm. This included two dry years and four years with above-normal rainfall. Contributions of growing season rainfall as percentage of the average normal rainfall were 167, 69, 106, 176, 55, and 147% for the six successive years; the 1973 being high surplus rainfall season while 1974 being a large deficit rainfall season.

Grain Yield

Data on grain yield of pearl millet on the basis of area cropped are given in Table 4 for different catchment to crop area ratios (hereinafter referred to as ratio). In 1970, yields for the control plot and plot with ratio 1.33 were the lowest, resulting from a 23-day long drought early in the season (Table 3) causing heavy mortality of seedlings on the control plot, and from large removal of productive surface soil for making bigger catchment in ratio 1.33. In this plot, with gradual improvement in soil conditions and with accumulation of residual effects of fertilizers applied in the first two seasons, yields, on the basis of area cropped, were found to be significantly higher than other water harvesting treatments. In water harvesting plot with ratio 0.5, a yield of 3717 kg/ha obtained in the 1971 season with below-normal rainfall was comparable to maximum yield of 3590 kg/ha recorded in a recent study (see Fig. 1 in Singh, 1984) on the same cultivar of pearl millet subjected to water supply and management practices least limiting to yield. This shows it was possible to obtain high yield of pearl millet in a year with below-normal rainfall at the research site using water harvesting. A reasonably good yield also from the control plot, which was comparable to yield from similar plot in the 1975 season with above normal rainfall, was primarily due to occurrence of showers at all the moisture-sensitive stages of crop growth.

The pearl millet crop failed in 1974 with below-normal rainfall, as also in 1972 with above-normal rainfall, since 90% of the growing season rains and 97% of total volume of runoff occurred in a short period from 15 to 25 Aug. 1972, whereas on water harvesting plots the yields ranging from 144 to 235 kg/ha in 1974 and from 600 to 900 kg/ha in the 1972 season were obtained. Thus, water

Table 3. Daily precipitation (P) and runoff (Q) received in growing season at the research site. Depth of water (D) in cropped area for various catchment area (Am) to crop area (Ac) ratios is not shown, since it can be estimated by identity : $D = P + Q \frac{Am}{Ac}$ Data on Q for 1970 and 1971 are not available

Date	P (mm)	Date	P (mm)	Q (mm)	Date	P (mm)	Q (mm)	Date	P (mm)	Q (mm)	Date	P (mm)	Q (mm)
1970		7/31	9		9/12	6.0	2.6	9/5	13.2	0.0	7/25	2.5	0.0
7/9	53	8/1	6		**1973**			9/8	19.0	8.0	8/6	14.5	7.7
8/3	11	8/3	3		7/3	11.4	4.2	9/9	2.0	0.0	8/7	15.5	6.1
8/4	15	8/12	43		7/6	12.2	11.3	9/10	8.4	4.2	8/8	3.5	0.0
8/5	25	8/28	24		7/8	13.7	10.8	**1974**			8/12	9.7	6.4
8/10	39	8/29	25		7/12	7.6	0.0	7/8	14.2	0.0	8/14	10.9	3.6
8/11	65	9/3	3		7/16	16.5	0.0	7/13	44.7	32.3	8/15	2.8	0.0
8/12	39	9/4	23		7/22	37.6	22.3	7/17	16.5	4.2	8/16	8.0	3.0
8/14	35	9/8	7		8/6	9.7	0.0	7/18	18.8	4.5	8/18	7.0	0.0
8/15	12	**1972**			8/8	17.9	0.0	7/21	4.6	0.0	8/19	7.9	0.0
8/18	42	7/2	5.2	0.0	8/9	2.1	0.0	7/22	17.0	4.0	8/23	3.0	0.0
8/19	10	7/7	3.6	0.0	8/10	56.2	31.3	8/20	15.0	0.0	8/28	4.0	0.0
8/24	27	7/10	6.8	0.0	8/15	25.0	6.6	9/26	31.0	19.2	8/29	6.5	3.9
8/25	26	7/11	11.2	4.4	8/16	10.7	0.0	9/27	2.8	0.0	9/3	5.7	0.0
8/31	12	8/15	5.0	0.0	8/17	19.6	8.4	**1975**			9/4	58.5	35.1
9/2	5	8/17	56.4	45.0	8/18	12.7	0.0	7/1	11.8	6.1	9/5	19.2	12.5
9/23	29	8/18	2.0	0.0	8/19	41.1	13.1	7/12	3.8	0.0	9/6	39.2	21.3
9/24	53	8/19	16.8	10.1	8/25	7.6	0.0	7/13	15.0	4.8	9/7	20.0	7.3
1971*		8/20	23.6	15.5	8/27	10.2	0.0	7/16	35.0	17.0	9/11	7.5	0.0
7/15	4	8/21	14.8	8.1	8/28	72.4	38.5	7/19	46.2	25.0	9/13	9.8	0.0
7/17	3	8/22	46.4	37.0	8/29	52.6	33.3	7/20	15.5	9.5	9/14	15.0	6.6
7/20	23	8/23	37.6	29.5	8/30	22.1	12.8	7/21	2.8	0.0	9/15	14.3	7.7
7/21	16	8/24	52.2	36.9	9/3	17.8	10.4	7/22	3.8	0.0	9/16	9.0	7.3
7/30	16	8/25	27.6	18.7	9/4	4.6	0.0	7/24	2.0	0.0	9/17	4.0	0.0

*51 mm of rain had occurred from 26 to 30 June 1971 harvesting system provided soil moisture conditions favourable for adapting dry-land system to imbalanced water situations.

Over four years, a maximum yield increase of 67% for water harvesting with ratio 0.5 over the control was measured (Table 4). In this ratio in which two-third of land area was cropped, production on a total area basis was similar to that obtained by cropping on the total area on flat surface, but tended to decrease linearly with increase in ratios (Table 5). Thus, 0.5 was the optimum catchment to crop ratio for the type of soil, climate, and surface sealing pond sediments. Water harvesting using this ratio would save one-third of the inputs required every season on a total area basis.

In the 1972 season with a 34-day long drought in the initial stage and once again at the later stage, large reductions in the earheads/m², length of earhead, no of grains/earhead, and grain weight/earhead (Table 6) were serious limitations to final grain yield on water harvesting plots. The no. of earhead-bearing plants per unit area being limited, and in the 0-90 cm soil depth the available soil water at the grain filling stage in water harves-

Table 4. Grain yield of pearl millet on the basis of area cropped, for different catchment to crop area ratios

Am/Ac	1970	1971	1972	1973	1974	1975	Mean over 1970, 71, 73 & 75
			kg/ha				
0.0	1080a*	2289a	0	2913a	0	2320a	2151a
0.5	3720c	3717c	597b	3505b	144a	3386b	3582c
1.0	2370b	2727b	367a	3237a	167a	3005b	2835b
1.33	1620a	3030b	898c	4433c	235b	3923c	3252bc

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test.

Table 5. Production of pearl millet on a total area basis, for different catchment to crop area ratios

Am/Ac	1970	1971	1972	1973	1974	1975	Mean over 1970, 71, 73 & 75
			kg/ha				
0.0	1080b*	2289b	0	2913c	0	2320b	2150b
0.5	2480c	2478b	396b	2352b	96	2424b	2434b
1.0	1180b	1364a	184a	1628a	84	1503a	1419a
1.33	694a	1299a	385b	1915a	101	1681a	1397a

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test.

Table 6. Yield components of pearl millet under four catchment to crop area ratios, for one erratic, and three good rainfall years pooled together

Yield components	Am/Ac			
	0.0	0.5	1.0	1.33
1972 rainfall				
Earheads/m2, no.	0	23	25	20
Earlength, cm	0	14.3	13.6	13.5
Grain weight/ear, g	0	5.0	3.7	4.7
Grains/ear, no.	0	716	570	807
1000-grain weight, g	0	6.9	6.5	5.8
1970, 1973, 1975 rainfall				
Earheads/m2, no.	26*a	32b	28a	27a
Ear length, cm	20.8a	20.7a	21.2a	21.0a
Grain weight/ear, g	10.1a	10.9a	11.0a	11.3a
Grains/ear, no.	1775a	1868a	1803a	1883a
1000-grain weight, g	5.7a	5.9ab	6.3bc	6.4c

*Means followed by the same letter in each row do not differ significantly at the 5% level by Duncan's multiple range test.

ting plots on sampling dates 22 and 29 Sept. measured 39 and 23 mm for ratio 0.5 and 90 and 35 mm for plots with ratio 1.0 and 1.33, hence the weight of 1000 grains was unaffected. Increased yield for water harvesting plots over the check in the seasons with good rainfall was through significant increase in the number of earheads/m^2 for ratio 0.5, and through a nominal increase in the number of grains/earhead alongwith significant increase in the 1000-grain weight for plots with ratio 1.0 and 1.33.

Crop Water Supply

Depth of water available from the rain and runoff in the four growing seasons has been presented in the previous paper (Singh, 1985). The 4-year average values and the yearly range of values presented in Table 7 were higher for water harvesting plots than for the check plots. Increased water supply was 75 to 198 mm for water harvesting over the check, ranging from 23 to 60 mm in the extremely dry season and 108 to 286 mm in the season with a good rainfall. In

Table 7. Depth of water supply to cropped area in the growing season

Treatment	4-year average	Range
	——mm——	
Check	310	117–528
Water harvesting		
0.5	385	140–636
1.0	459	162–743
1.33	508	177–814

dryland farming, storage of a few milimetres of water in the potential rooting zone of the soil means a difference between a crop and a crop failure.

Grain yield (Y, in kg/ha) response to the seasonal crop water supply (D, in mm) was evaluated for the low, medium and high rainfall seasons, and for the water harvesting treatments. Regression coefficients for ratios 1.0 and 1.33 did not differ significantly, hence a combined regression for these ratios was used. As seen from the regression equations given below, above variables were linearly related to each other.

Regressions for three rainfall conditions

$Y = 2.74D - 524$ (low rainfall)

$Y = 7.62D + 271$ (medium rainfall)

$Y = 4.20D + 666$ (high rainfall)

Regressions for catchment to crop area ratios

$Y = 6.89D - 827.9$ (0.0)

$Y = 6.04D - 417.4$ (0.5)

$Y = 4.94D - 356.5$ (1.0 & 1.33)

Water Use Efficiency

Water use efficiency (WUE) is generally expressed as production per unit of water used in evapotranspiration (ET). In dryland cropping system using water harvesting, ET is derived from the growing season rainfall and runoff. Together these sources total the crop water supply (D), the water of most concern to dryland farmers. The WUE values were thus calculated on the basis of kg grain/mm of seasonal crop water supply. Since the best fit line between Y and D was linear, $Y = a + b D$, it was possible to calculate water use efficiency from the relationship, $WUE = Y/D = b + a/D$, in which 'a' and 'b' are the constants of the regression lines given above. Predicted WUE are plotted, regardless of water harvesting treatments, in Fig. 5 for the low, medium, and high rainfall seasons. The intercept 'a' was negative for the season with low rainfall and positive for the medium and high rainfall seasons, therefore over the range of data points WUE tended to increcase, at a diminishing rate, with increase in D in the former condition and decline with increase in D in the latter condition (Fig. 5). At the 500 mm of D, 17 kg of grain could be expected for each 10 mm of D above threshold value of 197 mm in the low rainfall season, 55 kg of grain for each 10 mm of D above threshold requirement of 159 mm in the high rainfall season, and 82 kg of grain for 10 mm of D above threshold value of 36 mm in the medium rainfall season. This shows at the low yield level threshold requirement must have been the major part of the crop water requirement, but became less significant at the high yield level.

The highest 103 to 108 kg grain for each 10 mm of D expected in the medium and high rainfall conditions (Fig. 5) but at the low level of yield (1000 kg/ha) may not be desirable. Thus, to accomplish an optimum level of WUE while maintaining yield at an acceptable level, D at 350 mm appears to be desirable, since at this level 85 kg of grain for each 10 mm of D and a yield level of 2900 kg/ha could be expected in the season with medium rainfall, and 65 kg of grain for each 10 mm of D and a yield level of 2100 kg/ha could

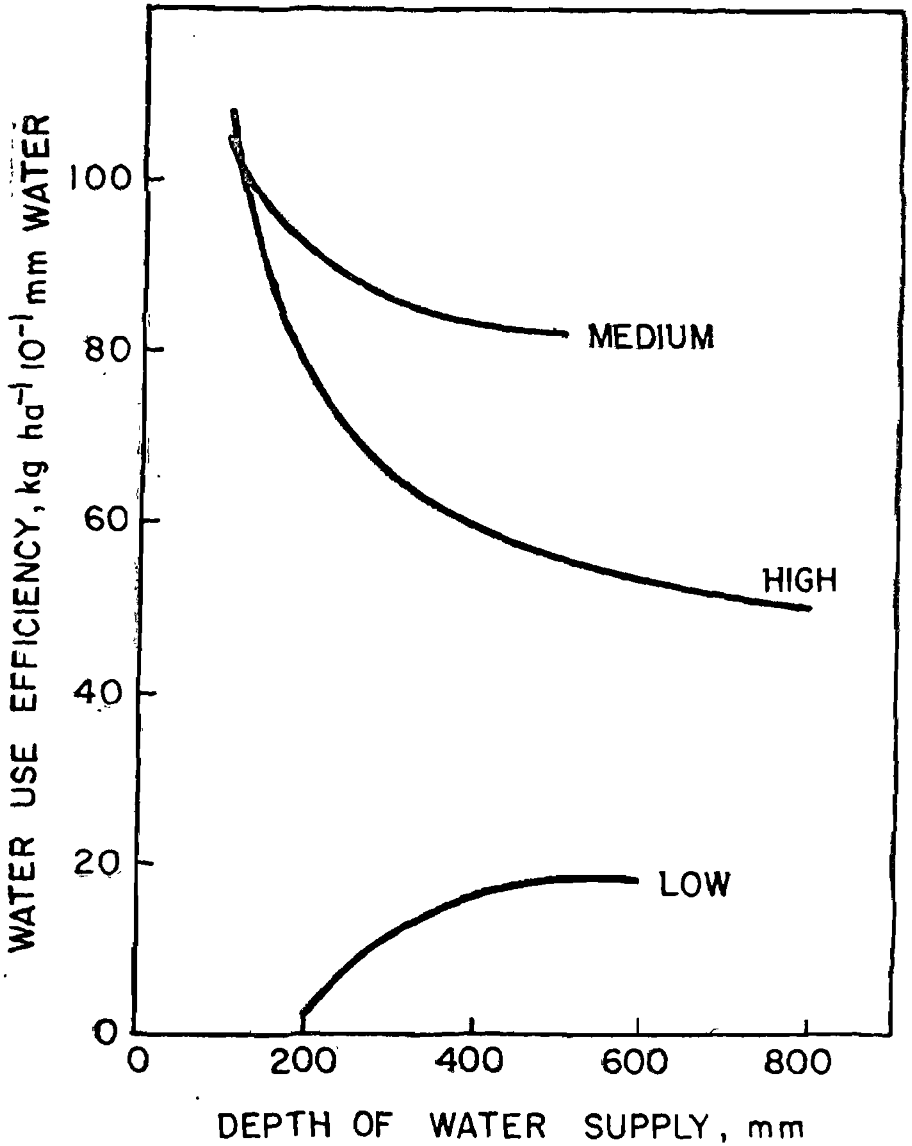

Fig. 5. The relationship between water use efficiency and depth of water supply (D) from rains and runoff for low, medium, and high rainfall seasons, as predicted by the Yield vs D regressions.

be expected in the season with high rainfall.

After reaching the soil rainwater is used as ET, percolated, lost as runoff, or stored in profile at time of harvest. The fundamental object of all systems of dryland farming is to reduce all losses other than crop ET. Runoff is responsive to management, whereas control on percolation and water on residual storage at time of harvest lies with the climate since these losses would depend on the amount and distribution of rainfall which are difficult to predict.

A decline in the efficiency of water use, being more pronounced in the season with high than with medium rainfall, could be attributed to loss on an average of 209.4 mm water as deep percolation and 143 mm of water in residual storage

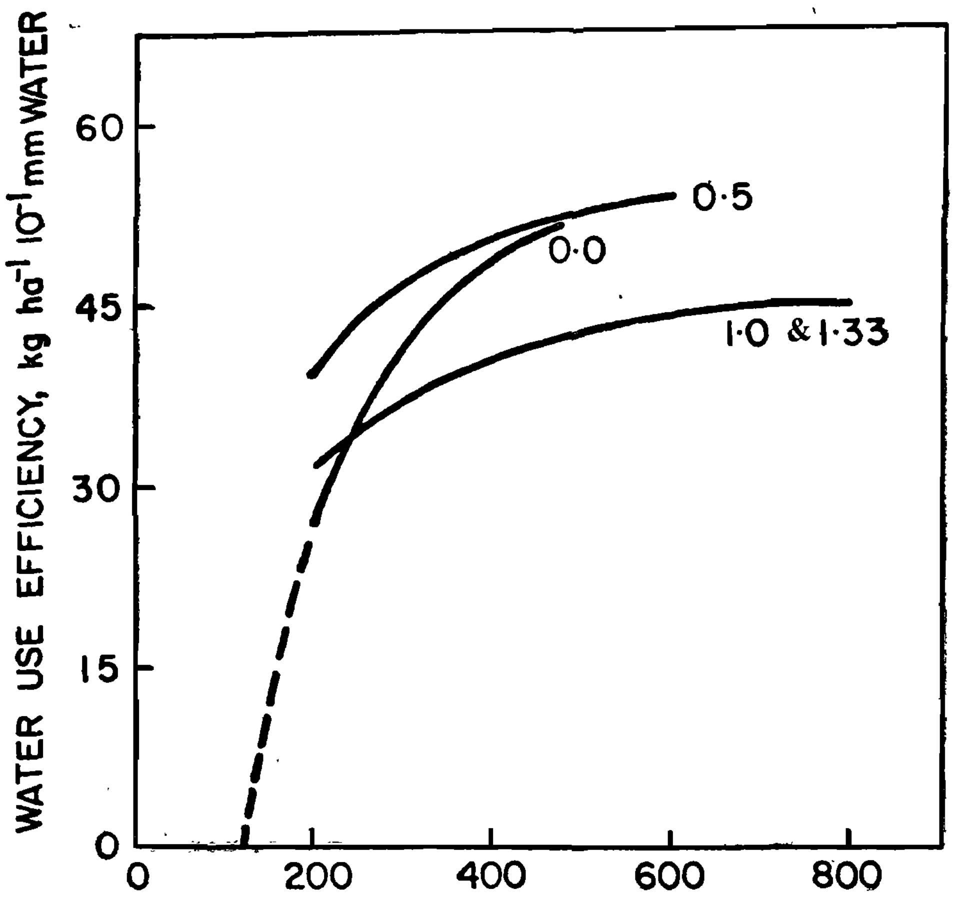

Fig. 6. The relationship between water use efficiency and depth of water supply (D) from rains and runoff for different catchment to crop area ratios, as predicted by the Yield vs D regressions.

at time of harvest resulting from 16 closely spaced showers during 15 Aug. to 10 Sept. in the high rainfall season of 1973. Corresponding losses of water as deep percolation and as residual storage were 65.4 mm and 143 mm resulting from 10 closely spaced showers recorded between 4 and 17 Sept. in the 1975 season with medium rainfall.

Intercept 'a' in the yield versus D regressions was negative for the check plot and the plots with water harvesting treatment, therefore a tendency for water use efficiency to increase with increase in crop water supply was observed (Fig. 6). Over the range of 200 to 600 mm of crop water supplies the WUE values were higher for water harvesting plot with ratio 0.5 than values for all other treatments, but in the 300-500 mm range the check plot showed higher WUE than the plots with ratio 1.0 and 1.33 Increased crop water supply becoming available from the increased volume of runoff on plots with wider catchment to crop area ratio could not be stored in the 0-90 cm profile of loamy sand and fruitfully utilized by the pearl millet crop. In all treatment plots the season ended with a wet soil profile at time of harvest. Loss of water as deep percolation varied, in order of 1975 to 1973 season, from 5 to 115 mm on the check plot, 53 to 196 mm on the plot with ratio 0.5, and 139 to 317 mm on the plot with ratio 1.33.

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Selection of Crops

S.D. Singh

ABSTRACT

Objectives were to select a group of adapted crops to provide security in food supply, ensure fertility recuperation by rotation with staple food crop like pearl millet [*Pennisetum americanum* (L.) Leeke], and enable contingent plan for delayed onset of monsoon. Crops were ranked according to their physical output, growth rate, water use efficiency, and yield (Y) reduction ratio : % Y reduction from maximum attainable yield (Ym) / % ET reduction from seasons ETm that produces Ym.

Physical outputs of pearl millet, grain sorghum [*Sorghum bicolor*(L.)Moench.], cowpea [*Vigna unguiculata* (L.) Walp.], mung bean [*Vigna radiata* (L.)Wilczek], and cluster bean [*Cyamopsis tetragonoloba* (L.)Taub.], in water harvesting plots were similar to the Ym from ETm plots. Pearl millet and grain sorghum provided the highest out put, which may be important for security of subsistence in desert agriculture. Among all study crops, pearl millet and cowpea showed the highest growth rates. Growth resumption after a drought when rain falls was fastest in pearl millet. With regard to yield reduction ratio, cowpea and cluster bean appeared to be environmentally the best adapted. However, pearl millet was most efficient in water use. From 20 cm of water use in the ET process it produced as much as obtained from 45 cm of water use on sorghum. Cluster bean was the poorest in the use of water. The picture concerning efficient use of water by the mung bean was also gloomy. Keeping above considerations in mind, pearl millet for high physical output, and cowpea and mung bean for rotatability with pearl millet appear to be the best crops for water harvesting system for this and similar arid regions of the world.

INTRODUCTION

Crop production by water harvesting is one of the package of practices for dryland farming. The growth characteristics sought in crop plants for water harvesting are early maturity, extensive root system, resistance to soil water stress, and efficiency in use of water. It is also important to select a group of adapted crops to provide security in food supply against total disaster, to ensure fertility recuperation by rotation with staple food crop, and to enable contingent plan for delayed onset of monsoon.

Pearl millet [*Pennisetum americanum* (L.) Leeke], grain sorghum [*Sorghum bicolor* (L.) Moench.], and grain legumes are the dryland crops basic to the lives of people in the Thar desert. Among these, hybrid pearl millet matures in 75 days, therefore, has an advantage of making the main part of its growth during the rainy season (July to September), over long-duration (110-120 days) hybrid sorghum, and cluster bean [*Cyamopsis tetragonoloba* (L.) Taub.] (Singh, 1985a). Both pearl millet and sorghum have extensive root system, which enables them to make large volume of water available to the plants (Kramer, 1969). Being the C_4 crop species, both are reported to have higher growth potentials (Arnon, 1975) and higher water use efficiency (Singh, 1985b), compared with legumes widely known for their least efficiency in water use (Leach, 1978). Both have ability to become dormant during droughts, but growth resumption after rain is much faster in pearl millet.

Some investigators (Gates and Hanks, 1967), on the contrary, have data to prove that legumes with deep root systems extract more water from deeper layers than shallow-rooted crops. Among legumes grown in the region, cluster bean has been found to be the most tolerant to water deficit (Singh, 1984). However, a crop resistant to water stress may not necessarily be eficient in the water use.

Preceding facts show that dryland crops mentioned above differ widely in their depth, extent and efficiency of rooting system, period of maturity, sensitivity to soil water deficits, ability to resume growth after drought when rain falls. These differences in adaptation to arid environments may produce large variations in crop response to water supply, yield potential, water use efficiency and merit for crop selection for water harvesting, which were evaluated in this study.

MATERIAL AND METHODS

Study was carried out during the 1972 to 1975 cropping seasons at the same site with the same number of treatments as are reported in First chapter of this series of papers. Hybrid grain sorghum [*Sorghum bicolor* (L.) Moench. cv CSH 1], mung bean [*Vigna radicta* (L.) Wilczek cv RS4], cowpea [*Vigna unguiculata* (L.) Walp. cv FS 68; C152 in 1972], and cluster bean [*Cyamopsis tetragonoloba* (L.) Taub. cv Sona] were included in the study. Pearl millet [*Pennisetum americanum* (L.) Leeke] was under trial since 1970. Each crop formed an independent experiment, and treatment effects on each were evaluated using a randomized block design with six replications.

Urea and diammonium phosphate supplied, respectively, 80 kg/ha of N and 26 kg/ha of P to grain sorghum. Grain legumes were grown in rotation with pearl millet and grain sorghum on residual fertility of N and P applied the preceding season. One-half of N with all the P were applied at the time of planting, and remainder one-half of N was top dressed with rain after a month or so.

For ranking crops according to their growth rate, water use efficiency, and yield (Y) reduction ratio : % Y reduction from the maximum level of attainable yield (Ym) / % ET reduction from seasonal ETm (the lowest ET value relating to Ym), another study was conducted in 1980 and 1981. The treatments included six water application levels, which were simulated through a line source sprinkler irrigation gradient system (Fig. 7). There was a single sprinkler line set in the center of the experimental area. So, there was no overlapping water application from the sides, but with sprinklers spaced 6.1 m apart down

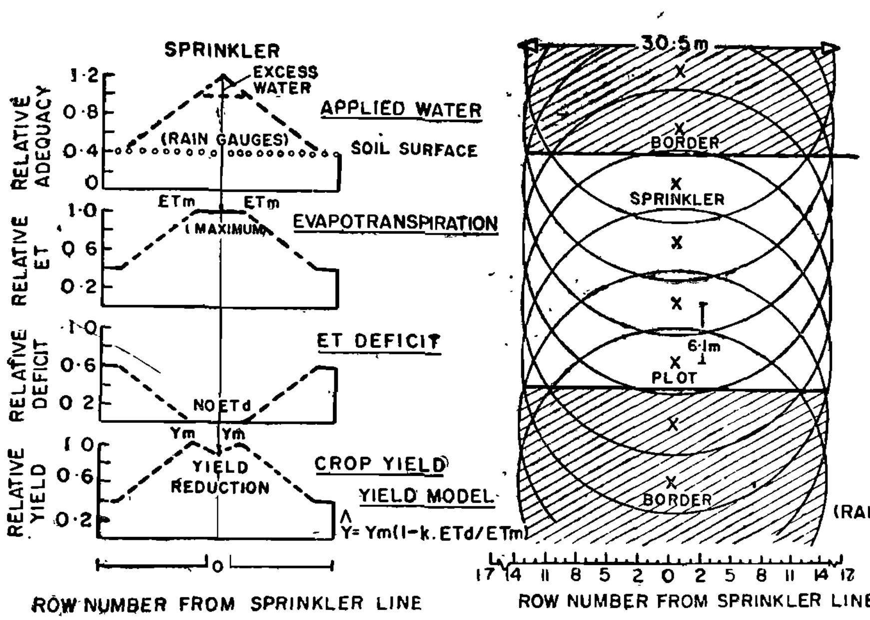

Fig. 7. Layout of line source sprinkler irrigation gradient system.

the line there was complete overlapping on both sides of the sprinkler line. All measurements were made within the fully overlapped area. This area began 9 m inside of the first and the last sprinkler on the line.

Six water application levels were measured on each side of the line, five within the sprinkler pattern and one beyond its reach. Rain gauges were maintained just above the plant canopy, adjacent to each neutron tube, in row numbers 2, 5, 8, 11, 14, and 17. Water level 6 never received irrigation water, hence it represented the rainfed conditions. At level 1 adequate water was applied when the available soil moisture in the 0-120 cm profile was depleted to 50%, to replace 100% of the crop water deficits. At the 2, 3, 4, 5, and 6 water application levels the percentage of soil water deficit replacement dropped linearly from the 100% at level 1 to virtually zero per cent at level 6.

Soil water content measurements were made at depths of 30, 60, 90, and 120 cm, and ET in each treatment was calculated using the soil water balance computation : $ET = \Delta S + P - R - D$, where ΔS is the change in soil water content in the root zone, P is precipitation/irrigation, R is the runoff, and D is deep percolation below the root zone.

The amount of water to be applied in a given period was determined by using a neutron probe to monitor soil water deficits that occurred at the end of each period under the 100% level of soil water replacement (i. e., at row No. 2). Water applications were made only at night and only when wind speed was less than 1 m/s. All crops were sown with onset of monsoon. The depth and frequency of irrigations depended on the amount and distribution of the growing season rainfall.

The water use efficiency, $WUE = Y/ET = b + a/ET$, was determined from the Y-ET relationship calculated from the data averaged over two seasons. The Y reduction versus ET deficits regression analysis determined the yield reduction ratio, from the Y and ET data transformed relative to Ym and ETm, taken as 100.

The net assimilation rate and crop growth rate were computed after Watson (1952), from the leaf area and dry matter data for the rainfed treatment.

RESULTS AND DISCUSSION

Tables 8 to 11 show the yields of study crops on a total area basis. As the percentages area under cultivation in catchment to crop area ratios 0.0, 0.5, 1.0, and 1.33 were, respectively, 100, 67, 50, and 43, crop yields on the basis of area cropped would reduce by the same percentages in estimating the level of production of a crop on a total area basis. Therefore, yields of grain sorghum, cowpea, mung bean, and cluster bean are given on the basis of area cropped only.

As in pearl millet, production by cropping two - third of the total area using water harvesting with a 0.5 catchment to crop area ratio was similar to the level of production from conventional cropping in the flat surface control. It follows that in our study crops and in soil and rainfall characteristics similar to this study site, catchment to crop area ratio at 0.5 appeared to be the optimum.

As this ratio increased, the productions were significantly lower in comparison to the flat surface control. In discussion of other aspects concerning crop choice, results emanating from water harvesting using 0.5 catchment to crop area ratio were used.

Yield Potential

With soil being good and management practices least limiting to yield, better soil moisture supply from rains plus runoff in the water harvesting system can set up conditions favourable for achieving yield similar to genetic yield potential of the crop.

To verify, the highest experimental yields of crops from water harvesting are given in Table 12, together with the maximum yields (Ym) recorded from the plots in which rain was simulated equal to potential evapotranspiration (ETm), in a 2-year study carried out separately at the same site in the years 1980 and 1981.

The yields of all crops in the water harvesting plots were similar to Ym. In cowpea and mung bean, difference between yields from water harvesting and the Ym from ETm plot was due to different varieties used in the two studies. Pearl millet and grain sorghum provided the highest physical output, which may be important in the subsistent desert agriculture as a source of staple food reserve for famine years. On the contrary, yields of grain legumes were lower, but they fetch high prices in the market, besides their acknowledged role in crop rotation and soil fertility recuperation.

Table 8. Yield of grain sorghum on the basis of area cropped under different catchment to crop area ratios

Am/Ac	1972	1973	1974	1975	Mean over 1973 & 75
			kg/ha		
0 0	0	3644a	0	2397a	3020a
0.5	422a*	4725a	0	3990b	4358b
1.0	318a	4431a	0	4785bc	4608b
1.33	442a	3816a	0	5787c	4802b

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test

Table 9. Yield of cowpea on the basis of area cropped under different catchment to crop area ratios

Am/Ac	1972	1973	1974	1975	Mean over 1973 & 75
			kg/ha		
0.0	171a*	1236a	0	330a	783a
0.5	365b	1763b	0	1126b	1445b
1.0	327b	1412a	0	1392b	1402b
1.33	193a	1770b	0	1531bc	1651b

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test

Table 10. Yield of mung bean on the basis of area cropped under different catchment to crop area ratios

Am/Ac	1972	1973	1974	1975	Mean over 1973 & 75
			kg/ha		
0.0	229*a	1073a	0	0	1073a
0.5	386b	1478b	132a	1819	1648c
1.0	533c	1400b	343b	742	1071a
1.33	512bc	1354b	714c	1535	1445b

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test

Table 11. Yield of cluster bean on the basis of area cropped under different catchment to crop area ratios

$\frac{Am}{Ac}$	1972	1974	1975
	kg/ha		
0.0	255*	0	0
0.5	350a	152a	1191b
1.0	330a	236a	1156b
1.33	299a	189a	891a

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's multiple range test

Table 12. Maximum yields of experimental crops

Crop	Days to maturity	Yield from water harvesting	Yield from ETm plot	ETm
	kg/ha			cm
Pearl millet	75	3582	3570	26.9
Grain sorghum	120	4358	4370	44.7
Cowpea	50	1445	1670	25.6
Mung bean	80	1648	1190	30.6
Cluster bean	110	1191	1210	NA

NA = not available

To relate yield (Y, in kg/ha) with the depth of water supply (D, in mm) from water harvesting plot, linear, exponential, and Cobb-Douglas functions were fitted. The coefficient of determination (R^2) given below showed that, in all crops, the yield was linearly related with the depth of water supply from rain plus runoff.

Re-arranged in deterministic form, linear functions for the study crops are:

	R^2		
	Linear	Exponential	Cobb-Douglas
Pearl millet :			
$Y = 1.332\ (D-12.5)$	0.96	0.85	0.90
Grain sorghum :			
$Y = 1.818\ (D-14.3)$	0.77	0.67	0.74
Cowpea :			
$Y = 0.565\ (D-12.1)$	0.93	0.78	0.82
Mung bean :			
$Y = 0.582\ (D-10.4)$	0.79	0.73	0.77
Cluster bean :			
$Y = 0.479\ (D-10.3)$	0.95	0.77	0.79

Threshold values of water supply that predictively would be used while yield be still zero was 103 mm in cluster bean and mung bean. The corresponding values were 125 mm in pearl millet and the highest at 143 mm for the grain sorghum crop. Singh (1985b) found 190 mm of water was necessary in the ET process before measurable yield of grain sorghum was obtained. In other crops like pearl millet, cowpea, and mung bean this requirement was a little over one-half. Thus in the production process of grain sorghum in the sandy arid plains of Rajasthan, about 45% of seasonal ETm was lost in the evaporative process without contributing anything to grain yield.

Crop Growth

Ability to become dormant when drought occurs and resume growth faster as the soil moisture becomes available is one *of the growth characteristics of all* crops adapted to dry land farming. To evaluate which of five subsistent crops grows faster, the net assimilation rate (NAR) and crop growth rate (CGR), which are the measure of gain in dry matter per unit leaf area per unit of time, were calculated (Table 13 and 14).

Table 13. Net assimilation rate (NAR) of five crops for the 1980 and 1981 seasons

Crop	*Weeks after planting*					
	3-4	4-5	5-6	6-7	7-8	8-9
1980			NAR, mg/dm^2/day			
Pearl millet	20.2	104.9	92.9			
Sorghum	53.6	87.2	124.7	27.3	3.4	178.6
Cowpea	78 0	55.4	41.4			
Mung bean	47.7	146.8	19.4			
Cluster bean	91.0	180.6	58.3	22.9		
1981						
Pearl millet	70.4	137.5	70.5			
Sorghum	107.5	47.2	49.7	49.5	169.9	
Cowpea	152.3	56.7	88.3			
Mung bean	135.3	50.4	4.5			
Cluster bean	115.0	127.5	62.6	6.2		

Table 14. *Crop growth rate (CGR) of five crops for the seasons 1980 and 1981*

Crop	Weeks after planting					
	3-4	4-5	5-6	6-7	7-8	8-9
1980			CGR, mg/dm^2/day			
Pearl millet	28.2	314.3	297.1			
Sorghum	12.9	52.3	137.1	32.8	4.5	553.7
Cowpea	7.8	11.1	8.7			
Mung bean	11.9	88.1	13.6			
Cluster bean	18.2	158.9	51.9	20.6		
1981						
Pearl millet	106.2	518.4	303.3			
Sorghum	64.5	105.2	138.7	141.1	576.1	
Cowpea	124.9	126.5	383.4			
Mung bean	33.8	77.1	6.9			
Cluster bean	29.9	117.3	70.1	10.4		

Data showed that NAR and CGR were linked with the amount and distribution of rainfall in the two seasons as also with the stage of plant growth. In pearl millet, the peak CGR value was found in week 4-5, whereas in cowpea and grain sorghum, peak CGR values of the order of 383, and 139 mg/dm² leaf area/day, respectively, were observed in week 5-6. After this until crop maturity, both NAR and CGR values in pearl millet, cowpea, and mung bean were negative, therefore are not given in the tables. Like pearl millet the highest CGR value in cluster bean was observed in week 4-5. However among all study crops pearl millet and cowpea showed the highest growth rates.

With onset of droughts (Fig. 8), both NAR, and CGR in sorghum tended to decrease until the next shower. In 1981, as adequate soil moisture became

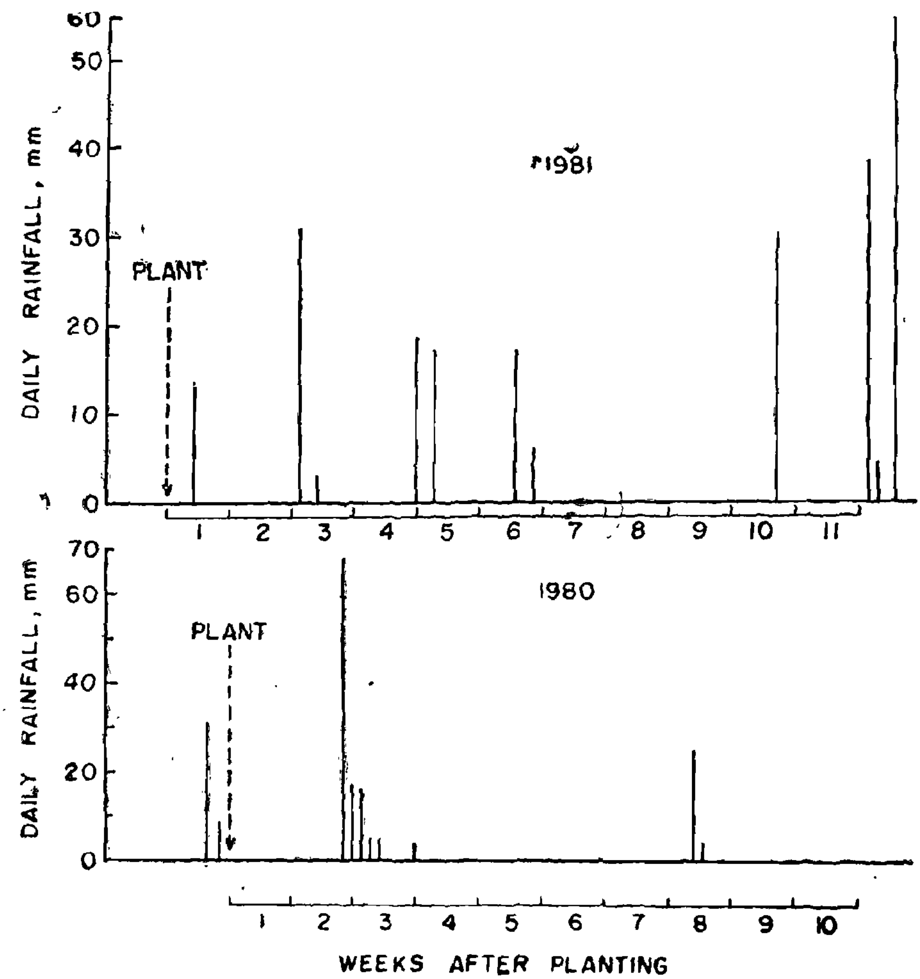

Fig. 8. Daily rainfall for 1980 and 1981.

available, sorghum resumed plant growth with 169.9 mg/dm^2/day NAR value and 576 mg/dm^2/day CGR value.

In another study, pearl millet was found to resume growth keeping almost the same rate of NAR but its CGR was 988 mg/dm^2/day (Singh, unpublished data). Thus, under similar growth conditions, as the soil moisture becomes available from rain following a prolonged drought, the pearl millet crop would resume growth much faster than shorghum.

By the time the soaking shower provided moisture relief to plants, cluster bean had forced matured whilst cowpea and mung bean had escaped drought by virtue of early maturity. Relative rates of growth resumption of these crops therefore could not be measured.

Yield Reduction Ratio

The slope of the yield reduction versus ET deficit, which corresponds to yield reduction ratio (YRR, i. e., % Y reduction/% ET deficit) termed by Stewart and coworkers (1975), may be useful for crop/varietal selection.

This slope, pooled over two years, was 1.20 for cowpea, 1.43 for cluster bean, 1.58 for mung bean, 1.62 for pearl millet, and 1.68 for sorghum, showing that, among the study crops, the cowpea and cluster bean crops were least affected by the soil water stress, mung bean and pearl millet were identical in tolerance to water stress, while yield reduction per unit of ET reduction was the highest in sorghum. Thus, cowpea and cluster bean appeared to be environmentally the best adapted. However, this alone may not be sufficient. The best index is productivity per unit use of water supply from rain plus runoff, which has been evaluated in the next section.

Water Use Efficiency

Water use efficiency (WUE) was expressed in terms of yield (Y) per unit of water use in evapotranspiration (ET). The relationships between Y and ET were linear in all study crops :

Pearl millet	$Y=2.15\ ET - 22.6$	$R^2=0.99$
Sorghum	$Y=1.65\ ET - 30.6$	$R^2=0.96$
Cowpea	$Y=0.77\ ET - 3.7$	$R^2=0.99$
Mung bean	$Y=0.62\ ET - 6.8$	$R^2=0.99$
Cluster bean	$Y=0.40\ ET - 5.0$	$R^2=0.89$

From these the WUE was estimated using the relationship : $Y/ET = b + a/ET$. Predicted WUE are plotted on Fig. 9, which shows a general tendency for WUE to decline, over the range of data, with a decline in ET.

Under water deficit conditions most field crops are known to have higher WUE; however in this study none of the crops showed higher WUE on the water stressed plots. This was obvious since the intercept 'a' was negative for all crops, a decrease in WUE as the ET decreased would be expected. In practice higher WUE on the water stressed plots is expected when yield is related to irrigation (IRR) with data points up to the level required for maximum yield (Ym) and Y versus irrigation water is convex.

Fig. 9 shows the use of water by pearl millet was most efficient. From 20

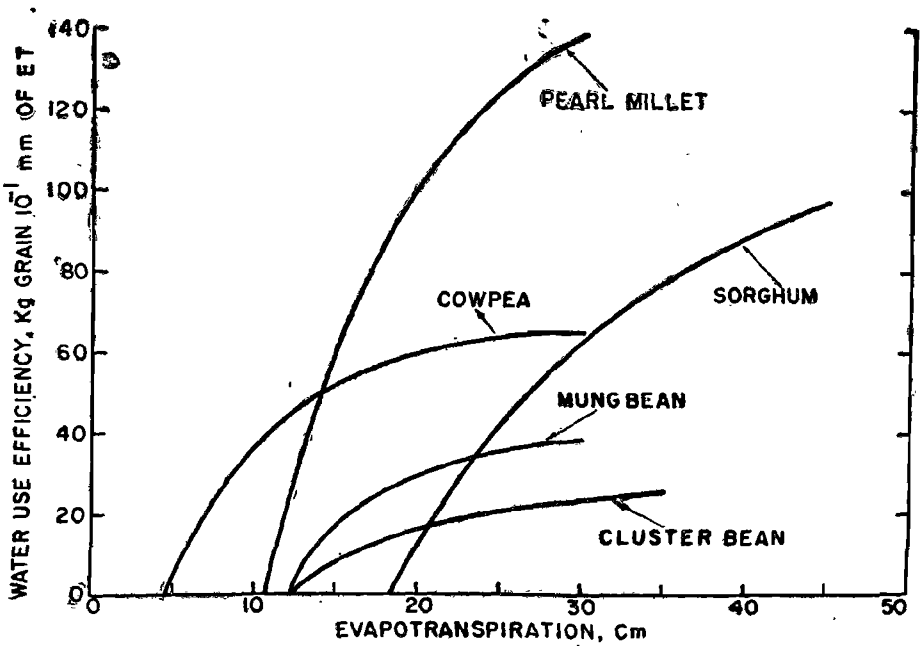

Fig. 9. Relationship between water use efficiency as predicted by the Y-ET regression and seasonal ET.

cm of water use in the ET process this crop was able to produce as much as was obtained from 45 cm of water use on sorghum. This is by far the most important reason why this crop occupies over 80% of cultivated area in the western Rajasthan. Cluster bean was the poorest among all crops in the use of water. The picture concerning efficient use of water by the mung bean crop was also gloomy.

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Integration of Planting Geometry

S.D. Singh and Mahander Singh

ABSTRACT

The paper deals with influence of integration of regular row (RR) and double row (DR) plant geometries into water harvesting system on yield and water use efficiency of pearl millet [*Pennisetum americanum* (L.) Leeke] found to be best suited to runoff farming. In the dry season with two cycles of prolonged drought in the critical stages of growth, a 22% yield increase in DR over RR was recorded. This increase was brought about in many ways, e g., suppression of early plant growth, a mild crop canopy microclimate, and conservation of water and nutrient by suppression of weeds in DR system. Besides, a 15% increased root length density in the surface layer was important for nutrient uptake whilst a 113% higher extension of root system to the deeper layer strengthened the plants to exploit the profile and use moisture therefrom. There was a higher water storage in the 120 cm profile, which supported the pearl millet crop during ear emergence and grain development period thereby increased significantly the number of effective tillers per unit area, the number of grains per ear, and the weight of 1000 grains In the seasons with above normal, well-distributed rainfall, yield was similar for both RR and DR plant arrangements.

INTRODUCTION

The light intensity required to maintain a maximum rate of photosynthesis by individual leaf is about 1500-2000 foot-candles (Arnon, 1975), while intensities in the field may reach 10,000 foot-candles (Donald, 1963). As the quantum of light is abundant, it may be desirable to adjust the crop water utilization to the available water supply by a regulatory mechanism on the crop canopy exposure to solar radiation that alone accounts for 80% of water use (Mukammal and Bruce, 1960) in evapotranspiration. The idea behind canopy compressions takes advantage of what the animal does to reduce the body exposure to cold by cuddling up in a foetal position.

Burch and Johns (1979) suggested the use of narrow row planting to balance transpiration with the available water supply, through faster accumulation of leaf area index beyond the level optimum for dry matter production. Studies by Chin Choy and Kanemasu (1974) on grain sorghum showed a decrease in water use by narrow row planting. On the contrary, Blum (1970) found that water use by hybrid sorghum was increased by increased plant density, while data from Bond *et al.* (1964)

showed a decrease in yield under narrow row planting.

Another way to reduce the crop canopy exposure to solar radiation is to change the spatial arrangement of plants from conventional regular row (RR) planting to a double row planting (DR) geometry. By bringing in the highest packing fractions of space between rows, DR planting may suppress early plant growth (Arnon, 1975; Blum and Naveh, 1976), increase root elongation (Haynes *et al.*, 1959), enhance senescence of mutually shading lower leaves in the row zone (Burch and Johns, 1978), and result in efficient use of Soil moisture. In studies by Blum and Naveh (1976) on grain sorghum grown on stored soil moisture, an increase in water use efficiency and yield was found. This may not hold true in the dry regions with a wide range of soil moisture resulting from intermittent showers in the season. Recently, Bebawi and Farah (1981) found that, under irrigated conditions of Sudan, more efficient use was made of water in RR plant arrangement.

The finding that plants make greatest growth in the direction of least interference (Ross and Harper, 1972) suggests that DR configuration creates more border rows, and border rows have been found to yield 13% more than adjacent inner rows of sunflower (Robinson, 1984). Apart from such benefit, border rows would greatly benefit when DR or even a triple row planting geometry (TR) would be integrated into water harvesting system with a catchment sloped on either side. In such integration, four of the six rows planted in a 3 m wide cropped are of DR and all six rows of TR system could benefit from runoffs from light rains that wet ribbon-like portion of the cropped area, all along the edge of the catchment.

The present study was conducted to evaluate the influence of an integration of plant geometry into water harvesting system on yield and water use efficiency of the crop found to be best suited to runoff farming.

MATERIAL AND METHODS

Studies were carried out for three years with pearl millet [*Pennisetum americanum* (L.) Leeke] BJ 104 cultivar as a test crop. Soil, climate, and agronomic details are given in the first chapter of this series of paper.

Planting in conventional 50 cm regular rows (RR) was compared with a double row (DR) configuration, i.e., 25 cm between rows within a pair, and 75 cm between row pairs, with intra row spacing of 10 cm in both. A paired plot design with 12 replications was used. Replications were arranged in a row on 96 m long by 3 m wide water harvesting plot, with 0.5 catchment to crop area ratio, and catchment covered with plastic, designed to integrate the two planting patterns (Fig. 10). Plots were thus 8 m long x 3 m wide. A triple row plant geometry with spacing of 30 cm between rows, 180 cm between pairs of triple rows, and 10 cm in the row was also included in the study in 1977. One row pair (25 cm between rows) of cowpea [*Vigna unguiculata* (L.) Walp.] was planted in the center of row pairs.

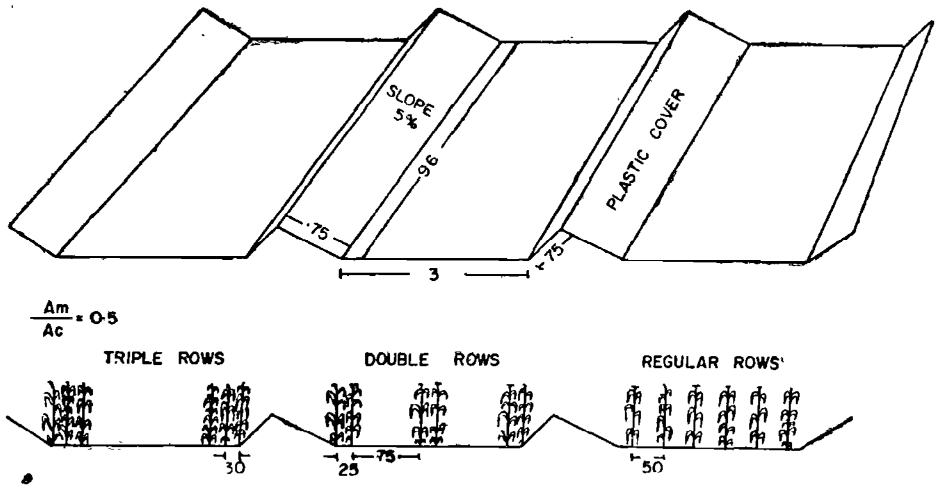

Fig. 10. Integration of regular, double, and triple row planting patterns into a water harvesting system Units are in meter

Crop received a dose of 15 t/ha of farmyard manure every other year, and 30 kg/ha of N as urea each year. Seeds were sown, with onset of rain, on 17 July 1976, 1 July 1977, and 14 July 1978 by a 6-row grain drill after adjustment in the spacing between seed coulters according to row arrangement in the three geometries. Desired plant population was achieved by thinning. At time of thinning ten 1 m row section was marked at random in both RR and DR for measurements of leaf area index and dry matter production at weekly intervals beginning two weeks after planting. Tiller development was recorded on three 1 m row length. For observation on crop-weed relation, weed dry matter was determined on ten 1 m^2 quadrates marked after crop emergence. By and large, weeds were annual, and cut for their dry weight at the flowering stage. Nitrogen in weed dry matter was determined by the micro-Kjeldahl method. LAI was determined by automatic area meter.

The 5 and 15-cm soil temperatures, relative humidity at the bottom of crop canopy, and albedo were recorded at 0700,0900, 1100, 1400, 1600, and 1900h on four consecutive days each year beginning 45 days after planting, using thermister, psychrometer, and albedometer, respectively. Root length per unit volume of soil was determined following Newman's technique (1966). Soil moisture determinations were carried out before and after each shower and between showers by the gravimetric method.

Crop was harvested 75 days after planting each year.

RESULTS AND DISCUSSION

Growing Season Rainfall

A total of 548.8 mm of rainfall from 28 showers, 226.8 mm from 26 showers, and 274.4 mm from 26 showers was received, respectively, in the 1976, 1977, and 1978 growing seasons. The first season was the season with 84% above-normal rainfall, whilst the latter two seasons experienced 24 and 8% below-normal rainfall. As seen from daily rainfall presented in Fig. 11 for the years in which leaf area index (LAI) and dry matter production (DM) were recorded, a 16-day long drought beginning 42 days after planting occurred in 1977, whilst a 18-day long drought at the tillering stage and a 22-day long drought at the grain development stage occurred in the 1978 season. LAI, DM, yield, and water use efficiency (WUE) were tied up with rainfall distribution.

Plant Growth

With better distribution of rainfall as in 1977, the highest LAI was manifest in DR planting pattern (Fig. 12). On the contrary, in 1978 with two cycles of drought, the greatest LAI was manifest

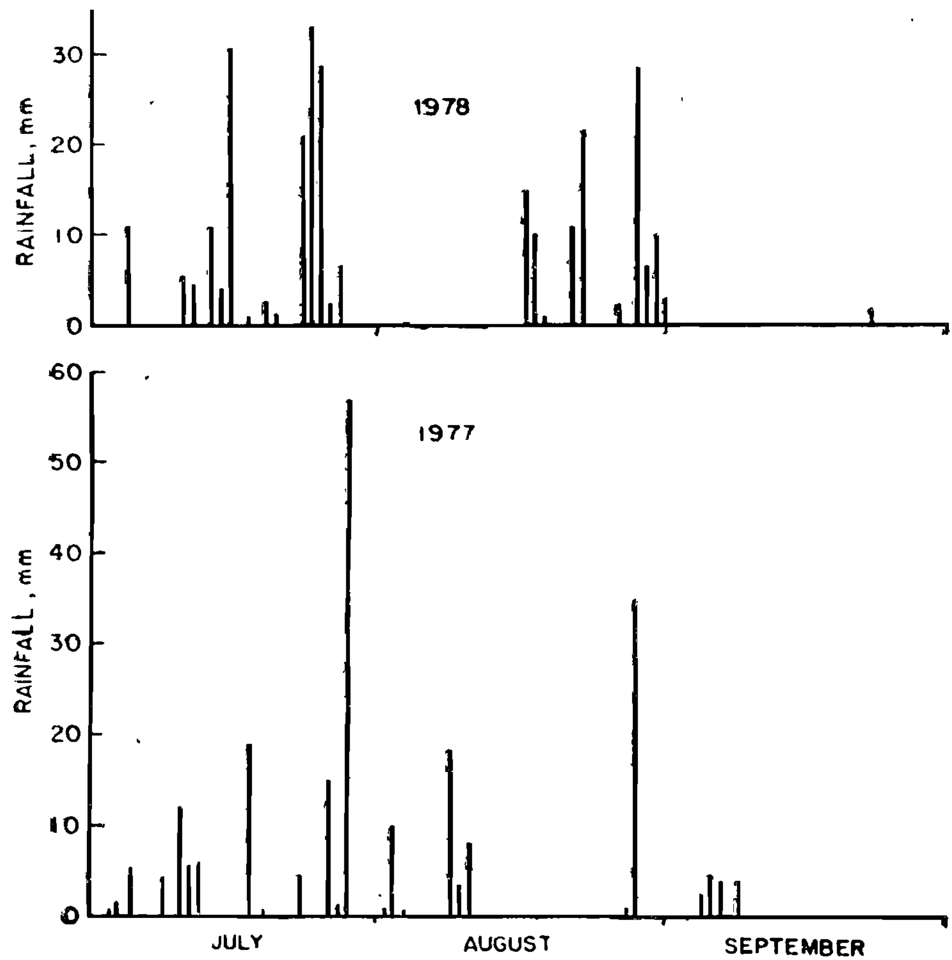

Fig. 11. Daily rainfall for the 1977 and 1978 seasons

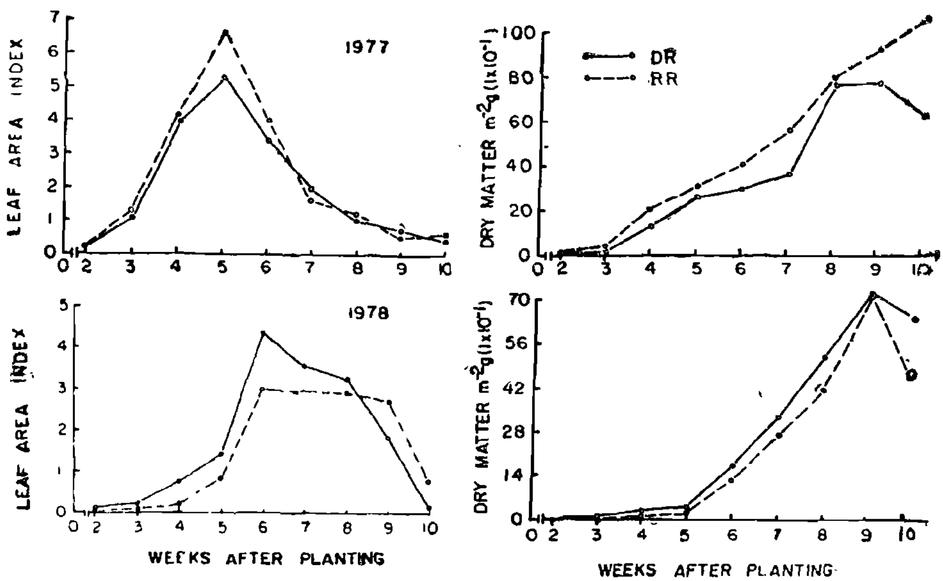

Fig. 12. Leaf area index and dry matter production by the pearl millet plants in RR and DR planting patterns for the 1977 and 1978 seasons

at the conventional planting pattern, but when a prolonged drought occurred at the fag end of the season pairing of rows tended to maintain a larger LAI. Dry matter production, by and large, showed similar trend as LAI. A decline in DM after reaching the maximum could be attributed to mechanical loss of the lower dry leaves.

These results indicate that reduced LAI and DM in the DR arrangement, as reported by Blum and Naveh (1976), would hold when the crop is grown on finite stored soil moisture, or the season has erratic distribution of rainfall. Nor our results for the 1977 season with well-distributed rainfall supported the finding (Bebawi and Farah, 1981) that changing the geometry of planting from conventional RR into DR would reduce the LAI and yield components of grain sorghum grown under irrigated conditions.

Data revealed that during the grand growth period in 1977 the number of shoots per unit area was higher in RR than in DR planting (Table 15). During the ear emergence and grain filling stage only the main shoot remained in both planting patterns; all tillers died owing to monopolisation by the main shoot for growth requirements especially for water. It follows that less tillering in DR in that year may have been basic to conservation of evapotranspiration in the critical moisture supply conditions. Further, it was observed that tiller development was faster in DR than in RR, and that in spite of a prolonged drought in the critical ear emergence and grain-filling stage in 1978 survival of ear-bearing tlllers/plant in this geometry

Table 15. Shoot development in pearl millet under RR and DR planting geometries

Geometry	Weeks after planting									
	1	2	3	4	5	6	7	8	9	10
	No/m²									
1977										
RR	20	24	80	90	98	92	72	20	20	20
DR	20	26	80	80	80	70	48	20	20	20
1978										
RR	20	20	60	60	60	60	60	40	20	20
DR	20	20	80	80	80	80	80	60	40	40

was twice as high, as compared with RR.

Influence of planting pattern was reflected in the root morphology. Root length per unit volume of soil was higher by 15% in the top 15 cm of soil layer, and by 113% in the 90-120 cm of soil in DR than in RR (Fig. 13). Higher root length density in top layer is significant where maximum water and nutrient yields are important, and that in the lower layers could increase water extraction from greater depths.

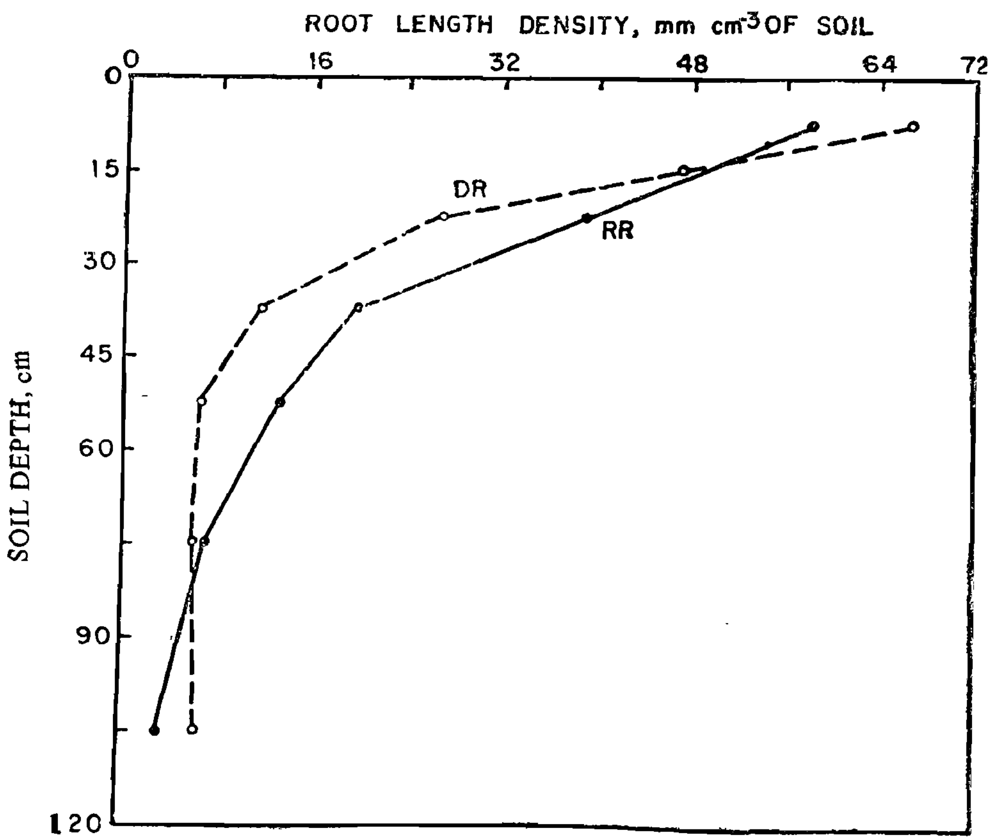

Fig. 13. Root length density of pearl millet recorded at the heading stage, 1978

Crop Microclimate

Thick lamilar layer in the row zone resulted in early canopy development. With a heavy crop canopy, the soil was kept cooler, the crop provided insulation to maintain a higher humidity amidst crop canopy, and there was higher reflectivity of energy in DR, as compared with RR planting (Table 16).

between-row-zone, rather it can facilitate weed control between row pairs by inter-cultivation.

Removal of N by weeds from DR plot was considerably less in comparison to RR plots (Table 17). As these data show, more water and nutrients might have been available to plants in DR planting geometry.

Table 16. Day average soil temperature, relative humidity, and albedo under RR and DR planting patterns. Each value is the average of the 1977 and 1978 seasons

	RR	DR
Soil temperature, °C		
5 cm	31.6	30.7
15 cm	32.3	30.5
Humidity, % (bottom of canopy)	65	69
Albedo (day avg.)	22	24

Weed Suppression and N Removal

Judged from weed dry matter per unit area, the plants in DR planting system were significantly ($P < 0.01$) better able to suppress weeds than in RR (Table 17). Degree of suppression was significantly ($P = 0.05$) greater between rows than between row pairs. These results indicate that DR planting did not introduce any problem of weed control

Yield

Yield was related with the amount and distribution of rainfall in different years. In the seasons with above normal, well-distributed rainfall, it was similar for both geometries of plant arrangement, whilst a 22% yield increase in DR over RR was recorded when the season was dry, two cycles of prolonged drought at the critical stages of growth (Table 18).

Table 17. Weed dry matter (DM) and N removal by weeds in the RR and DR planting geometries. Each value is the mean of 11 quadrates

Planting pattern	1977		1978	
	DM	N	DM	N
	kg/ha			
Regular rows	704	10.2	794	7 9
Double rows	210	3.2	370	6.3
Between rows	84		160	
Between row pairs	126		210	

This increase was brought about in many ways. The DR geometry of planting resulted in suppression of early plant growth. It maintained a mild crop canopy microclimate. By suppression of weeds, it resulted in the conservation of water and nutrients. Increased root length density in the surface layer is important for nutrient uptake whilst better extension of root system to the deeper layer strengthened the plants to exploit the profile and utilize moisture therefrom. There was a higher water storage in the 120 cm profile (Fig. 14). The soil moisture so saved on account of these favourable features supported the pearl millet crop during the ear emergence and grain development period, thereby increased

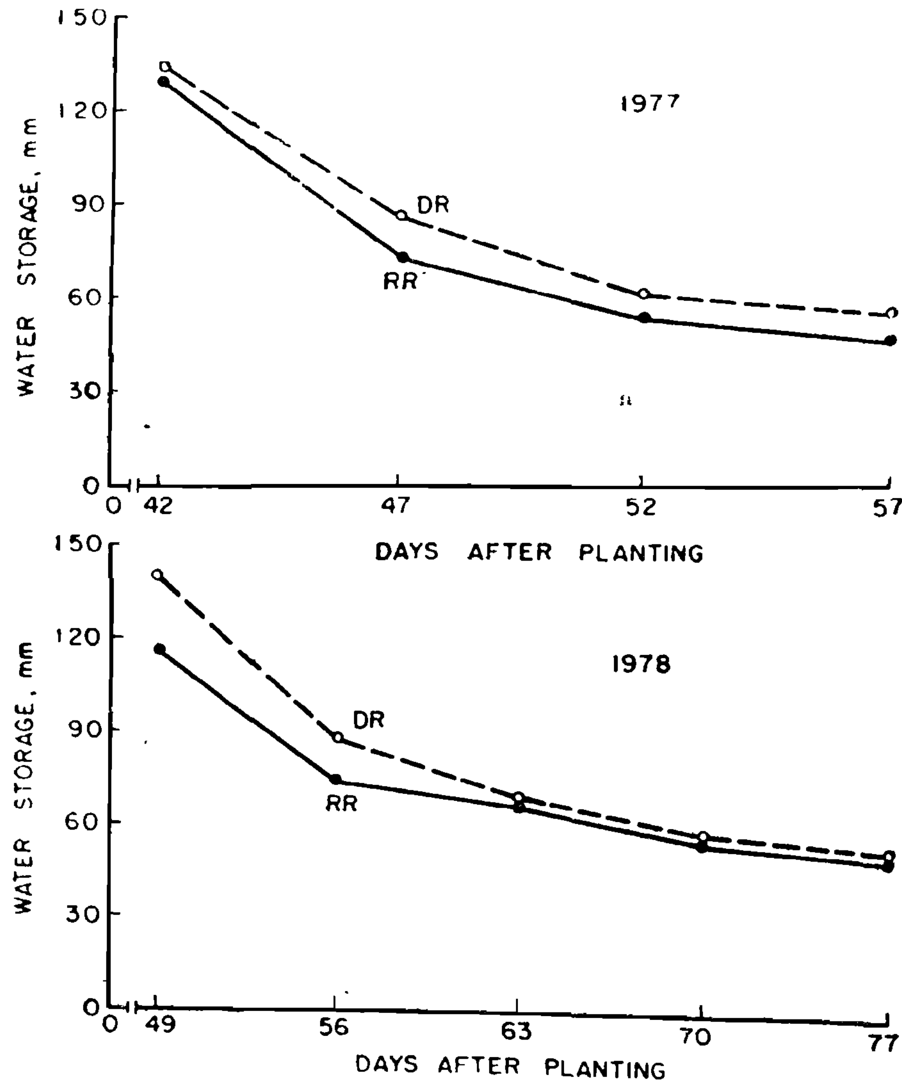

Fig. 14. Water storage in the 120 cm profile in RR and DR for the years 1977 and 1978

Table 18. Effect of planting pattern on pearl millet

	1976		1977		1978	
	RR	DR	RR	DR	RR	DR
No. of shoots/m^2	na		20	20	20a*	40b
Grain/ear, no.	2000	1994	2128b	1972a	1633a	2016b
1000-grain wt., g	7.7	7.2	5.8	4 4	5.3a	6.5b
Yield, kg/ha	2914a	2732a	2574a	2609a	2329a	2839b

na = not available

*Means followed by the same letter in a row did not differ significantly at the 5% level of probability by t-test

significanty the number of effective tillers per unit area, the number of grains/ear, and the weight of 1000 grain (Table 18). The 22% yield increase did not involve any additional expense, since plant arrangement is a non-monetary technology.

Contrary to the observation by Blum Naveh (1976) in dryland grain sorghum [*Sorghum bicolor* (L.) Moench.] grown on stored soil moisture, when significant yield increase takes place DR planting would not reduce the number of ears/plant, since plants made larger growth in the open space between row pairs (Ross and Harpér, 1972) and escaped much of interplant competitions. Neither would there be any decrease in grain weight of individual shoot until the development is limited to two tillers on the main shoot (Table 19).

Integration of twin-rows into a water harvesting system brought a 31% yield increase over the row pair located midway between the row pairs (Table 20).

Table 19. Grain weight (mean of 30 plants sampled at random) per single shoot of pearl millet taken from DR plant arrangement in 1977

Shoot	Yield of			
	main shoot	tillers		
		1	2	3
	g			
Single	21.6			
Double	24.2	17.1		
Triple	24.7	18.3	19.4	
Quadruplicate	22.3	18.2	14.7	12.0

Table 20. Yield of pearl millet from the center row pair versus mean yield from two row pairs located near the catchment on either side of the plot

Row position	1976	1977	1978	Overall
	kg/ha			
Center of the plot	2428a*	1885a	1954a	2089a
Near catchment	3379b	2441b	2373b	2731b

*Means followed by the same letter in a column do not differ significantly at the 5% level of probability by the t-test

Plastic cover could produce runoff from light rains, sufficient to wet a ribbon-like area on the plot surface adjacent to catchment only, thereby improving the water storage in soil profile (Fig. 15). Water storage so increased provided a *safe guard against droughts.*

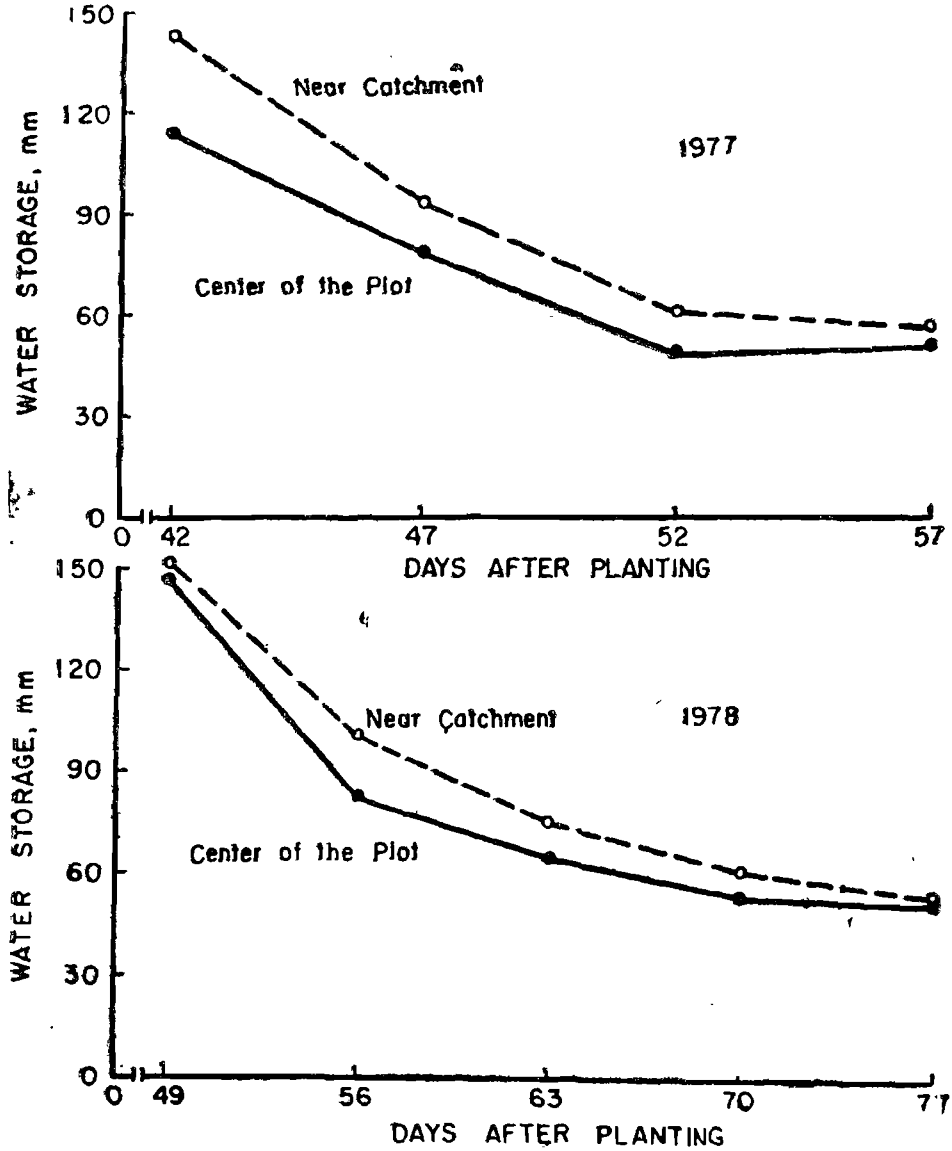

Fig. 15. Moisture storage in the 120 cm profile taken in the row pair when located in the center of the plot and that near the catchment, 1977 and 1978

A triple row configuration did not confer any yield advantage over DR system, except a marginal production of 260 kg/ha from cowpea planted in twin-rows midway between the pairs of triple rows.

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Integration of Management Practices

S.D. Singh and Mahander Singh

ABSTRACT

The paper aims at achieving higher production, over local practices, by integrating into water harvesting the better crop variety, judicious use of manure and fertilizer N, and better crop husbandry practices like reduced tillage, weed control, and planting geometry. Local practices consisted of cultivation of local variety of pearl millet [*Pennisetum americanum* (L.) Leeke] in regular row geometry, on the flat surface control, and without preparatory tillage and weed control. Improved package of practices enhanced yield from 398 kg/ha for local practices to 2845 kg/ha, with yield gap of 2447 kg/ha. Better crop husbandry practices filled this gap by 902 kg/ha. Hybrid seed, manuring, and water harvesting together contributed 2035 kg/ha. After having followed the better husbandry, the better seed, manure and water harvesting plugged the yield gap by 1544 kg/ha, and in the presence of these practices in the resource pool the better husbandry contributed 412 kg/ha to the total yield of pearl millet.

Better management practices yielded 63 to 66% more in cowpea and 22 to 146% more in mung bean, over local practces. Yield of pearl millet was 62% higher in rotation with cowpea than in rotation with mung bean.

INTRODUCTION

Water harvesting considerably improves the depth of water supply in the rooting zone of crop (Singh, 1985). But relying on water alone for higher production will not be logical unless it is combined with other factors of production (see Fig. 3 in Singh and Mann, 1979). Among these factors, management practices such as water harvesting (Singh, 1985), good germ plasm (Patel, 1974), adequate supply of plant nutrient (Chundawat and Shekhawat, 1972; Singh, 1976), reduced tillage (Singh *et al.*, 1973), better cropping system (Shankarnarayan and Singh, 1985; Singh et al., 1985), weed control (Malik *et al.*, 1980; Singh *et al.*, 1983), have acknowledged link with higher yield and water use efficiency by pearl millet. Information is, however, lacking about the effects of integration of these components of production on the yield and water use efficiency of pearl millet.

To quantify this the study was designed to integrate into water harvesting system the plants, soil, water, and fertility management, including the practice of conservation of evapotranspiration (ET). High yielding cultivar, planting pattern, and rotative cropping (pearl millet was grown in rotation of cowpea FS 68 and mung bean S8) were components of plant management. Area of water management relates to innovative technology of water harvesting. Fertility management included the combination of organic and inorganic sources of nutrient supply. The ET conservation was achieved through timely removal of additional weed canopy. Under soil management, we included the reduced tillage, i.e., planting after a harrowing. These were included in the category of improved technology.

Improved technology was compared with conventional technology. By conventional technique we mean cropping on the flat surface control without manuring, weed control, and plant protection. The RSK variety of pearl millet, RS4 of mung bean, and Pusa Do Phasali of cowpea were used as local strains. In one of such conventional control, one weeding was done.

MATERIAL AND METHODS

Studies were conducted on pearl millet [*Pennisetum americanum* (L.) Leeke], cowpea [*Vigna unguiculata* (L.) Walp.], and mung bean [*Vigna radiata* (L.)Wilczek] for three consecutive years - 1976 to 1978. Experimental site, soil, and climatic characteristics are described in the first chapter of this series of paper.

Test crops were grown in two water harvesting systems, i.e., ridge-furrow system (50 cm wide ridge alternated by 50 cm wide furrow) and inter-plot water harvesting with 0.5 catchment to crop area ratio, and on flat surface control. Ridges and catchments were covered with plastic. A set of compacted earth catchment was also included.

Crops were sown in double row configuration in ridge-furrow system of water harvesting, and in 50 cm regular row and double row in the inter-plot water harvesting and flat surface control, with intra row spacing of 10 cm in pearl millet and 8 cm in legumes. Spacings of 25 cm between rows within the pair and 75 cm between row pair were maintained in the double row system of planting.

The treatment combinations were the same as are given in abbreviated form in Tables 21 and 23. Depending upon the research need contemplated, a few additional treatments were incorporated in last two years of the study. A randomized block design with four replications was used. Abbreviation used denoted : CP = catchment covered with plastic, C = compacted earth catchment, RFP = ridge -furrow with ridges covered with plastic, RF = ridge - furrow without plastic, FC = flat surface control, W = weeding, Wo = no weeding, F = manure and fertilizer applied, Fo = without manure and fertilizer, RT = reduced tillage, i.e., planting after harrowing, PP = plough-to-plant, IV = improved variety, RR = 50 cm regular rows, DR = double row planting with spacings of 25 cm between rows and 75 cm between row pairs.

The pearl millet crop received 30 kg/ha of N as urea each year, apart from 15 t/ha (air dry basis) of farmyard manure every two years. Crops were sown with onset of monsoon, on 17 July 1976, 1 July 1977, and 14 July 1978 by a 6-row grain drill, and desired plant population was achieved by thinning. Legumes were grown in rotation with pearl millet on residual fertility. Hence the effect of rotation on yield and water use efficiency of pearl millet could be measured from the second season on. In 1976, the effects of RFP and RF were discussed only.

Nodulation studies on roots escavated from 1 m row length were carried out in cowpea and mung bean 24, 34, 44, and 54 days after planting. For the comparison of reduced tillage and plough-plant, germination percentage and weed number and weed dry matter in these two sets of tillage methods were taken. Weed number and dry matter were determined 18 days after sowing on 30 quadrates each of 0.5 m^2.

Nitrogen removal by weeds was determined by the micro—Kjeldahl method. Weed study in fallow land was also carried out.

Crops of pearl millet, cowpea, and mung bean were harvested 75, 50, and 80 days after sowing, respectively.

RESULTS AND DISCUSSION

Plastic Versus Compacted Earth Catchment

Compared with crop yield for compacted earth catchment, plastic catchment brought 30% improvement in yield of pearl millet (Table 21).

Watershed Zone on Catchment Versus Watershed Zone on Ridges

With plastic cover on it, the watershed zone on catchment should provide nearly identical opportunity to the crop to take advantage of all light rains as may do the watershed zone on ridges. Yields of pearl millet, as a result, were similar under plastic sealed catchment and plastic sealed ridges. Watershed on ridges with and without plastic also produced similar yields (Table 21), there was therefore no need to cover the ridges with plastic. Compared to compacted earth catchment, a 19% yield increase under the treatment of watershed on ridges without plastic cover showed higher possibility of runoff from ridges than from compacted earth catchment.

Like compacted earth catchment, ridges and furrows were made initially in the first year. In subsequent years, only furrow bottoms received tillage by tiller. As the yield in ridge-furrow system tended to decline from 2818 kg/ha in 1976 to 1941 kg/ha in 1978, it seems that compaction under ridges inhibited root proliferation. If this hypothesis holds good, ridges and furrows will have to be constructed in every season.

Another noteworthy point was this. In 0.5 catchment to crop area ratio, one-third area of the field goes to catchment, therefore one-third saving in time and all production inputs takes place every season. It could pay off the catchment construction cost in one or two seasons.

We now return to analyse whether the sum total of benefits accrued from individual practices will be more or the total benefits if two of agronomic practices complement each other ? It may be seen that contribution of a given agronomic practice, say manuring, when it interacts with weeding might be a little different from the value when it interacts with water harvesting. For instance, contribution of manuring in interaction with weeding was 1082 kg/ha as against

Table 21. Yield of pearl millet under various combinations of agronomic practices, 1976-78

1976		1977		1978	
Treatment	Yield, (kg/ha)	Treatment	Yield, (kg/ha)	Treatment	Yield, (kg/ha)
CP+DR+W+F+RT	3087e*	CP+DR+W+F+RT	2609e	CP+DR+W+F+RT	2839d
C+DR+W+F+RT	2377d	C+DR+W+F+RT	2338d	C+DR+W+F+RT	2753d
CP+DR+W+Fo+RT	1844c	C+DR+W Fo+RT	1199bc	C+DR+W+Fo+RT	1571c
CP+DR+Wo+F+RT	2779e	C+DR+Wo+Fo+RT	1243bc	C+DR+Wo+Fo+RT	861b
CP+DR+Wo+Fo+RT	1407b	CP+RR+W+F+RT	2574e	CP+RR+W+F+RT	2773d
CP+RR+W+Fo+RT	1892c	C+RR+W+F+RT	2338d	C+RR+W+F+RT	2330cd
CP+RR+Wo+F+RT	2627d	C+RR+Wo+F+RT	2141d	C+RR+Wo+F+RT	1937c
CP+RR+Wo+Fo+RT	1913c	C+RR+W+Fo+RT	1054b	C+RR+W+Fo+RT	2029c
RFP+DR+W+F+RT	2834e	C+RR+Wo+Fo+RT	1010b	C+RR+Wo+Fo+RT	954b
RF+DR+W+F+RT	2818e	RF+DR+W+F+RT	2329d	RF+DR+W+F+RT	1941c
FC+RR+Wo+Fo+LV+RT	508a	FC+DR+IV+W+Fo+RT	1199bc	FC+DR+IV+W+Fo+RT	576ab
		FC+DR+IV+W+Fo+PP	823b	FC+DR+IV+W+Fo+PP	189a
		FC+RR+LV+Wo+Fo+RT	317a	FC+RR+LV+Wo+Fo+RT	369a

*Means followed by the same letter in a column do not differ significantly at the 5% level of probability by the LSD test

1052 kg/ha interaction with water harvesting. Hence, in quantification of contributions to yield of agronomic practices this much little variation seems acceptable.

The overall additive yield from manuring and water harvesting by plastic catchment was 1460 kg/ha campared with complementary yield figure of 2845 kg/ha. Similarly, the complementary yield when double row planting geometry interacted w'th water harvesting using plastic was 457% higher than sum total of their indvidual contributions.

Area of Fertility Management

Combination of 15 metric tons/ha of farmyard manure plus 30 kg/ha of fertilizer N (hereinafter manuring) resulted in 69 to 85% increase over no manured plot, in yield of pearl millet in three years (Table 22). A substantial increase in the production of this crop was thus possible by optimum manuring under dryland conditions.

Conservation of Evapotranspiration (ET)

To conserve ET by elimination of additional weed canopy, weeding program was integrated into the production system. Beneficial effects of manuring were interrelated with weeding operation (Table 22). In the unweeded plots, increases in yield of pearl millet due to manuring were 1036, 930, and 1229 kg/ha in the three successive years. Corresponding increases in absolute value terms in the weeded plots were 1392, 1139, and 742 kg/ha.

Contributions of manuring and weeding to yield of pearl millet when added together were 1588, 1096, and 1635 kg/ha in 1976, 1977, and 1978, respectively. The corresponding yields due to interaction between these practices were 3260, 2338, and 2542 kg/ha (Table 22). Thus, the total benefits accrued from complementary effect of manuring and weeding were greatly larger than additive yields from individual practices.

In unweeded unfertilized plots, yields tended to decline in successive years (Table 22) which could be attributed to crop-weed competition tending to increase due to weed seeds multiplication.

Better Genotype and Tillage

To verify the farmers' common belief that local variety of pearl millet out yields the hybrid in their conventional method of cultivation, recommended variety of hybrid for the region (BJ 104) was incorporated in last two years of the study.It was found that absolute additive and complimentary yields were similar

Table 22. Influence of manuring on yield of pearl millet in relation to weeding (W) and no weeding (Wo). Fo = no manuring, F = manuring, 1976-78

	1976			1977			1978		
	Wo	W	Mean	Wo	W	Mean	Wo	W	Mean
	kg/ha								
Fo	1672	1868	1770	1243	1199	1221	908	1800	1354
F	2728	3260	2994	2173	2338	2256	2137	2542	2340
Mean	2200	2564		1708	1769		1522	2171	

showing that tillage requirement was not influenced by crop genotypes.

In the plots receiving reduced tillage, yields of improved varieties BJ 104 ranged from 576 to 1199 kg/ha, compared with 317 to 369 kg/ha yield of local variety; the increase being 56 to 278%.

The yield of improved variety from the plot receiving reduced tillage was on an average 380 kg/ha greater than that from the plough-planted plot. This difference was significant.

Analysis into the causes for this lower yield revealed that seedling emergence percentages on the plots receiving the two tillage treatments were equal - 62%. Study of weed count and weed dry matter in 1 m x 1 m 30 quadrates 18 days after planting showed 841, 208, and 56 weeds/m^2 in untilled fallow, plough-to-plant, and reduced tillage treatments, respectively. The corresponding weed dry weights were 336.4, 55.8, and 3.3g/m^2. Nitrogen removal by weeds from fallow land was 57.2 kg/ha. Hence it was heavy crop-weed competition early in the season that resulted in significantly a lower yield in the plough-to-plant treatment.

Yield Gap Between Scientific and Local Technology

Cultivation of local variety of pearl millet RSK, in regular row geometry, on the flat surface control and without preparatory tillage, manuring, and weed control yielded 398 kg/ha (Fig. 16). Adoption of improved package of practices increased yield (for the same amount of 3-season average rainfall) from 398 to 2845 kg/ha. Thus, yield gap between better and poor technology was by 2447 kg/ha.

Without use of fertilizer, hybrid seed, and water harvesting, better crop husbandry practices comprising one reduced tillage, one weeding, and double row planting geometry filled this gap by 903 kg/ha. Without better husbandry, contribution of hybrid seed, fertilizer, and water harvesting together was 2035 kg/ha. However, after having followed better husbandry, the hybrid seed, fertilizer and water harvesting plugged the yield gap by 1544 kg/ha, and with the presence of these practices in the resource pool the better husbandry contributed 412 kg/ha to the total yield of pearl millet.

Yield of Cowpea and Mung bean

Adoption of improved management practices yielded 63 to 66% more in cowpea and 22 to 146% more in mung bean, over local practices (Table 23).

Compared with the flat surface control, yields of cowpea varied from no increase in 1978 to 44% increase in 1977, whilst increases in that of mung bean varied from 30 to 38%. In the ridge-furrow planting system, yield of cowpea was similar to that from compacted earth catchment. It was 63% higher over 538 kg/ha under bare catchment, in 1978. On a total area basis, total productions of cowpea and mung bean were significantly higher in the ridge-furrow system of planting than in compacted earth catchment.

Other than the 1977 season when the yield of cowpea for regular row (RR) was significantly 16% greater than double row (DR) planting geometry, the

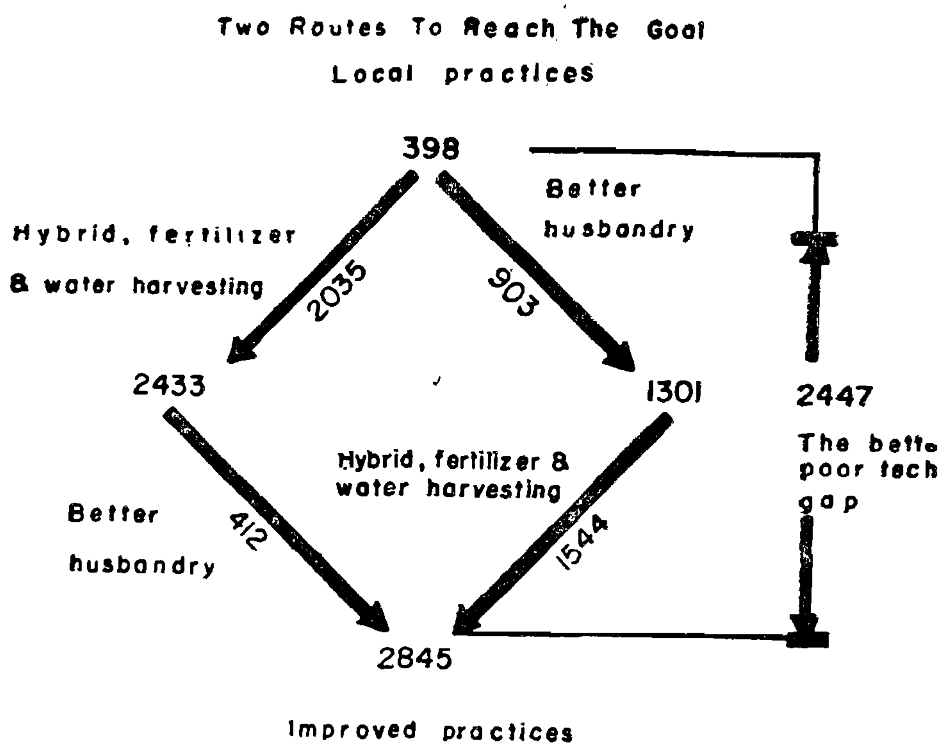

Fig. 16. Effects of integration of management technologies into the system of water harvesting on yield and water use efficiency by pearl millet

yields of cowpea and mung been for RR and DR were similar (Table 23).

Nevertheless, DR planting geometry may prove advantageous from standpoints of the following growth parameters which may be significant in subnormal rainfall years. With regard to crop-weed relations, weeds in DR were suppressed more between rows than between row pairs. On account of differential suppressions of weeds in the two planting geometries, weeding, by and large did not contribute to yield of both crops in DR. But in RR weeding resulted in 15% more cowpea in 1977, and 18 to 162% more mung bean in both of the study years (Table 23).

Rooting patterns of the two crops also differed. In 30-60 cm layer of soil profile, the root length in cm/cm^3 of soil volume was 1.3 in DR as against 0.8 in RR. Comparing the two crops, it was found that in 0-30 cm layer of the soil profile, the root lengths on 8/1 and 8/20 were, respectively, 1.9 and 3.2 in cowpea, and 0.5 and 2.1 in mung bean. Therefore, water and nutrients must had to move to a lesser distance in cowpea planted in DR than RR in the mung bean crop before entry into the system.

Unlike pearl millet, the yields of these pulses both in plough-planted and planting after a tillage treatment were the same. It implies that the characteristic

Table 23. Yields of cowpea and mung bean as influenced by integration of agronomic practices into water harvesting system, 1977 and 1978

Treatment	Cowpea		Mung bean	
	1977	1978	1977	1978
	kg/ha			
C+DR+IV+W+RT	1581b*	538b	1278bc	713c
C+DR IV+Wo+RT	1573b	511b	1210b	511b
C+RR+IV+W+RT	1829c	539b	1557cd	753c
C+RR+IV+Wo+RT	1591b	462b	1417c	287a
RF+DR+IV+W+PP	1531b	877c	1203b	545b
FC+DR+IV+W+PP	959a	530b	924a	584b
FC+DR+IV+W+RT	1101a	567b	929a	549b
FC+RR+LV+Wo+RT	972a	324a	1051a	290a

*Means followed by the same letter in a column do not differ significantly at the 5% level of probability by Duncan's multiple range test

of crop canopy and the rooting system may have some relevance in crop-weeds competitive phenomenon. While shallow rooted annual weeds possibly subsisted upon the upper soil layer, the legumes by their deep root system fastered on nutrients and moisture if available at some depth below the surface soil. Another noteworthy point was this. In plough-to-plant, where intense weed competition did not allow the crop to come up, loss of nutrients by weed flora, in one season amounted to 18 kg/ha of N and 5 kg/ha of phosphorus. Upon decay and lixiviation, a part of nutrients so robbed of may return to soil in recycling process, ungrazed ; or be permanently lost to the field when grazed by animals.

Leguming Effects of Cowpea and Mung bean on Succeeding Pearl Millet

In 1978, pearl millet was grown separately in the plots in which cowpea and mung bean were grown the preceding year. It was found that the yield of pearl millet was 62% higher in rotation with cowpea than in rotation with mung bean. Data in Table 24 show that in both the crops the nodule number and weight showed an increasing trend with the plant age but tended to decline towards the reproductive stage. The number of nodules/plant and their dry weight were relatively higher in cowpea than mung bean in the early stages of the plant growth. Nodules at vegetative stage have been found to be more active and

Table 24. Nodulation in cowpea and mung bean 24, 34, 44, and 54 days after planting averaged over the 1977 and 1978 seasons. Each value is the mean of 13 observation plants excavated from 1 m row length

Unit/Plant	Cowpea				Mung bean			
	24	34	44	54	24	34	44	54
Total nodules, no.	23	47	32	23	13	33	48	35
Effective nodules, no.	22	39	26	10	12	28	45	28
Dry Wt. of nodules, g	0.04	0.05	0.06	0.04	0.01	0.04	0.06	0.05

showed higher nitrogenase activity than at reproductive stage. Further the nitrogenase activity/plant of cowpea has been found to be markedly higher than mung bean under the field conditions. Hence it suggests that the better nodulation status in cowpea in the vegetative stage might have resulted in greater nitrogen fixation resulting in the better growth of the succeeding crop.

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Runoff Efficiencies of Four Catchment Sealing Materials and Water-Nitrogen Interaction

S.D. Singh, Y.V. Singh and R.C. Bhandari

ABSTRACT

The use of linear regression analyses of precipitation versus yield of runoff showed the runoff efficiencies and threshold values, i.e., minimum rainfall needed to produce runoff, of four water harvesting catchments namely compacted earth catchment, pond sediment, janta emulsion (ESSO product), and plastic. The interaction between each soil moisture condition established by four water harvesting catchments and nitrogen applied to pearl millet [*Pennisetum americanum* (L.) Leeke] at 0, 40, 80, and 120 kg/ha emerged significant. The crop receiving 80 kg/ha of N showed the highest yield in plastic and the next highest yield in janta emulsion catchment. Nitrogen at 40 kg/ha was about the optimum dose for other two catchments. The study has also provided answer to three most important questions related to water harvesting, i.e., development of low cost land shaping technique, system of farming level areas without changing the surface topography, and low cost method of sealing the catchment.

INTRODUCTION

Water harvesting research over one and a-half decades at this Institute has shown considerable potential for increase and stability in crop yields. Nevertheless, many problems need answer before transfer of technology to farmers takes place.

The problems, according to Wittmus (1963), include : (1) development of low cost land shaping technique, (2) development of systems of farming level areas without changing the surface topography, and (3) development of a low cost method of sealing the catchment area.

Orientation of sloping catchment into two directions (Fig. 17) solves much of the problem of low cost land shaping. Ridge-furrow system of cropping (Fig. 18) appears to be answers to the problem of 'development of system of farming level areas without changing the surface topography'. Use of indigenously available pond sediments to cover sloping catchment appears to be an answer to the problem like 'development of a low cost method of sealing the catchment'.

Of various materials tried to induce runoff (Myers, 1961; Chinn, 1965; Frasier and Myers, 1970; Rauzi et al., 1973), threshold retention of pond sediment catchment was found to be 4.5 mm (Singh, 1985). Of 80 years of rainfall record at Jodhpur, 50% of the total number of showers occur as showers $\leq$ 4.5 mm.

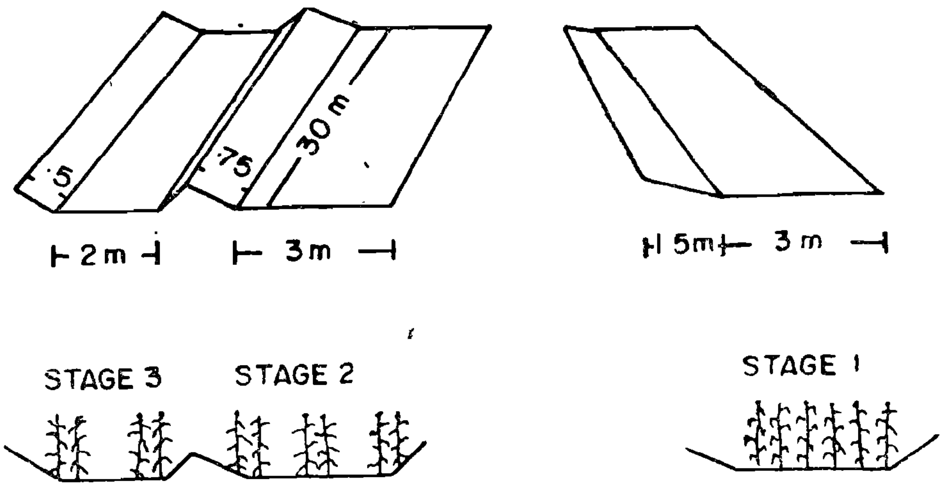

Fig 17. Stages of improvement in technology for concentration of rainwater in a level area

In Indian part of the Thar desert, over 60% of the area has sandy to loamy sand soils. During rain the dispersion of aggregation takes place. The dispersed soil particles of silt and clay re-orient themselves to form strong bonds upon drying of the wet soil (Gupta and Nagarajarao, 1982). And infiltration rate is reduced. For these reasons, it may not be necessary to apply any impervious cover on the catchment. However, untreated catchment may have still higher threshold-retention and lower efficiency of runoff.

As the degree of imperviousness and threshold rainfall influence the runoff efficiency of a water harvesting technique, plastic with zero threshold and 100% runoff efficiency (at least for one or two years), and janta emulsion (ESSO product) with 2.2 mm threshold and 88% catchment efficiency (Murthy *et al*, 1978) were incorporated in the study.

As different catchments would produce different amounts of runoff, and as water and fertilizer N complements each other (Singh *et al.*, 1976; Singh and Mann, 1979), it would be necessary to find out the optimum dose of N for each type of catchment.

The objectives were (i) to find out water harvesting efficiencies of four catchment sealing treatments, and (ii) determine the optimum requirement of N for pearl millet [*Pennisetum americanum* (L.) Leeke] under each soil moisture condition established by four catchment sealing materials.

MATERIAL AND METHODS

Soil type, climatic characteristics, and construction design and slope of catchment, and rainfall and runoff measurement were the same as described in first chapter of this series of papers. As catchment to crop area ratio of 0.5 was found to be optimum, this ratio was maintained. To facilitate and economise land shaping, the width of catchment was reduced from 1.5 m to 1 m and crop

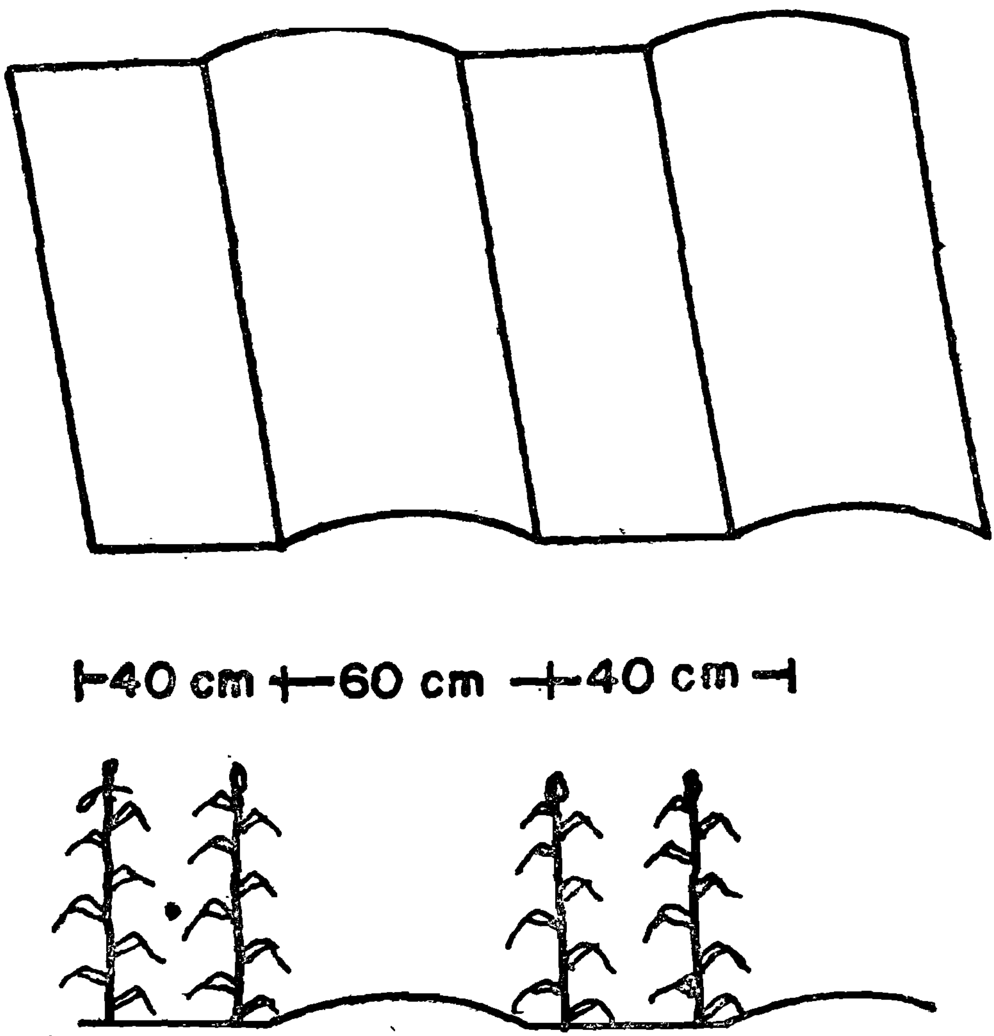

Fig 18. Concentration of runoff in furrows

area width was reduced from 3 m to 2 m.

Treatment details are as follows : (i) Flat surface control, (ii) Compacted earth catchment. In this the soil was compacted to a depth of 10 cm increasing the density to 2 g/cm^3; (iii) Application of finely ground pond sediments to a thickness of 1.25 cm on compacted earth catchment and re-compacted, (iv) Cover of black plastic sheet of 1000 gauge (0.4 kg/m^2) over compacted earth catchment and (v) Janta emulsion (ESSO product) at the rate of 2.7 kg mixed with 0.4 liter of kerosene/m^2 was applied over compacted surface. Catchment and crop area was 48 m long. It was divided into four equal plots and urea to supply 0, 40, 80, and 120 kg/ha of nitrogen was applied in each water harvesting treatment, including the flat surface control. Five water harvesting treatments were factorially combined with 4 N levels, replicated four times.

Pearl millet [*Pennisetum americanum* (L.) Leeke] cv BJ-104 was planted on 6th July 1985 and 25th July 1986 by four tined grain drill. Fifty centimeter inter row and 10 cm intra row spacings were maintained. Desired plant population was achieved by thinning.

Table 25. Daily precipitaton (P) and runoff (Q) in the 1985 and 1986 seasons

Date	Precipitation	Runoff (Q)			
		Plastic	Janta emulsion	Pond sediments	Compacted earth catchment
1985			————mm————		
7/16	40 0	39.1	39.1	34.0	25.5
7/18	6.2	6.2	6.2	3.4	2.6
8/3	3 2	3.2	3.2	0.9	0.0
8/4	26.5	26.5	26.5	23.0	18.3
8/5	25.0	25.5	23.8	20.0	17.0
8/13	8.0	7 2	6.8	6 0	4.7
Total	108.9	107.7	105.6	87.3	68.1
1986					
7/25	45 6	43.0	37.0	41.7	28.1
7/28	44 0	39 1	38.3	34.0	25.5
7/29	40.8	37.4	33.2	31.5	23.4
7/30	3.0	3.0	2 6	0.0	0.0
7/31	1.0	0.0	0.0	0.0	0.0
8/7	1.0	0.0	0.0	0 0	0.0
8/9	2.8	0.0	0.0	0.0	0.0
8/12	12.6	11 5	11.1	10.2	6.0
8/16	25.0	19.1	17.0	16.3	14.5
Total	175 8	153 1	139.2	133 7	97.3

Six daily rainfall events in 1985, and 9 in that of 1986 (Table 25) were used for analysis of regression equation, runoff efficiency, and threshold value of each water harvesting treatment. Response to water supply from rain plus runoff was measured in terms of grain yield.

RESULTS AND DISCUSSION

Efficiencies of Water Harvesting Treatments

Regression equations, correlation coefficients, runoff efficiency after threshold, and threshold retention are presented in Table 26. The coefficients of correlation between precipitation(P) and runoff (Q) approached unity (0.99 to 0.999), which is typical of high efficiencies of catchments treated with four sealing materials.

The first year, plastic covered catchment yielded runoff after threshold close to 100%, followed in order by janta emulsion, pond sediments, and compacted earth catchment with runoff efficiencies of 98.5, 90.0, and 68.4%, respectively. Threshold retention of plastic-treated catchment was negligible. In a study by

Table 26. Regression equation, correlation coefficients, runoff efficiency after threshold, and threshold retention for four water harvesting treatments, 1985 and 1986

Treatment	Regression equation	Correlation coefficient	Runoff efficiency	Threshold
1985			%	mm
Plastic	Q=0.9936P—0.0614	0.999**	99.4	0.06
Janta emulsion	Q=0.9852P– 0.2819	0.999**	98.5	0.29
Pond sediments	Q=0.8999P—1.7834	0.999**	90.0	1.98
Compacted earth catchment	Q=0.6842P—0.8431	0.996**	68.4	1.23
1986				
Plastic	Q = 0.9207P—0.7002	0 995**	92.0	0.76
Janta emulsion	Q=0.8342P–0.5896	0.994**	83.4	0 71
Pond sediments	Q=0 8779P—2 7104	0 988**	87.8	3.09
Compacted earth catchment	Q=0.6327P—1.7415	0.998**	63.3	2.75

Frasier (1975) over a period of four years, average threshold rainfall of plastic catchment was 0.2 mm and corresponding runoff efficiency was 92%.

The second year, four surface sealing materials in above order yielded 92.0, 83.4., 87.8, and 63.3% runoff, and threshold retention of 0.76, 0.71, 3.09, and 2.75 mm. In this year, decrease in runoff efficiencies, and increase in threshold retention could be attributed to shrinkage in plastic surface due to annual variations in temperature and and solar radiation. It was erosion from other catchments that increased threshold retention thereby decreasing the runoff efficiencies after threshold. Minor cracks were also observed over janta emulsion and pond sediment treated catchments.

In first chapter of this series of paper, runoff efficiency after threshold was 84% and threshold retention was 4.5 mm, in the first year of pond sediment treatment to a thickness of 5 mm.

This catchment received pond sediments cover to a thickness of 1.25 cm.

Low Cost Land Shaping
Grain Yield

Yields of pearl millet for the 1985 and 1986 seasons are shown in Table 27. Depth of water supply from rain plus runoff is also given under each catchment. As seen from the data, increase in water supply by a few mm brought considerable increase in yield. As a result, interaction between type of catchment and N levels emerged significant. In both years, catchment covered with plastic and crop receiving 80 kg/ha of N showed the highest yield. The same level of N brought the next highest yield in janta emulsion catchment. With regard to other catchments, including flat surface control, by and large, N at 40 kg/ha seemed better.

This table further showed that the depths of water supplies were much greater in 1986 than in 1985, whilst grain yields in the latter season were three to four times larger compared with those for the 1986 season. This could be attributed to concentration of 76%

Table 27. Effect of significant interaction between water harvesting catchement and level of N for the seasons 1985 and 1986. $D = P + Q \frac{Am}{Ac}$, where D = depth of water supply from rain plus runoff, P = precipitation, Q = runoff, Am = catchment area, and AC = crop area

	Sealent	Plastic	Janta emulsion	Pond sediments	Compacted earth catchment	Flat surface	Mean
1985	D, mm	163	162	153	143	109	
	kg N/ha			kg/ha			
	0	875*h	500bc	703f	498bc	199a	555
	40	1227k	888h	1042j	801g	488b	889
	80	1940l	1063j	625e	754fg	556d	987
	120	1240k	965i	895h	909h	528bcd	907
Mean		1320	854	816	740	443	
1986	D, mm	252	245	243	224	176	
	kg N/ha			kg/ha			
	0	444h*	176a	240c	156a	211b	245
	40	451h	269d	269d	460h	300e	350
	80	536i	491i	244cd	353fg	366g	398
	120	358g	365g	445h	329f	279de	355
	Mean	447	325	299	325	324	

*Means followed by the same letter in the body of table do not differ significantly at the 5% level of probability by Ducan's multiple range test

of the seasonal precipitation within five days after onset of monsoon in 1986 (Table 25). It shows that distribution of rains was more important for the crop than the amount in a season.

As shown in preceding papers of this series, 0.5 catchments to crop area ratio in integration with double row planting geometry proved the best. In stage 1 of improvement in technology for concentration of rainwater in a level area (Fig. 17), this ratio was obtained by maintaining 1.5 m wide catchment and 3 m wide crop area. It required more of man and machinery hours.

In stage 2, catchment area remained the same but the slope of the catchment from the top was oriented to two directions. As a result the width to be maintained reduced to one-half-0.75 m. In stage 3, crop area was reduced to 2 m, so that entire plant population receive the benefit of ribbon like wet area adjacent to catchment, apart from width of catchment further reducing from 0.75 to 0.5 m (Fig. 17). To this width earth work was made by disc-plough and shaping and rolling by manual labour. In this way, the technology provides answers to the problem : 'development of low cost land shaping technique'.

System of Farming Level Area Without Changing Surface Topography

Let us now proceed to final solution to the problem : 'development of a system of farming level areas without changing the surface topography'. As discussed in the preceding papers of this series of papers, cropping using water harvesting having catchment to crop area ratio of 0.5 and catchment sealed with pond sediments proved to be the best treatment. It was taken as a base for comparison with the system of farming cultivated areas without any needs of land shaping.

In the new system, Massey Furguson seed drill (company's name is given only for convenience of readers) is used to plant in a double row system (Fig. 18). Furrowers are attached in front of seed coulters to open furrows about 20 cm deep. And planting is done at the bottom of furrows in the same operation (Photo 1), after harrowing with planker attachment. This operation is done every season.

Photo 1. Seeding attachment in furrower

Table 28 presents the yield data of pearl millet from pond sediment catchment and that from the system of farming level area in which planting and furrowing was done in one go. The crop failed due to delayed onset of monsoon in 1972, and scanty rainfall in 1974, whilst experiment on planting in furrows could not be carried out in the 1971 season.

In four out of six seasons, the mean differences were highly significant. Compared with pond sediment, a yield increase ranging from 37 to 77% was obtained from the new system of planting. Rainwater concentration took place in furrows. Shankarnarayan and Singh (1985) have reported that a better technology is one that increases yield at least by 30% or be able to double the yield compared with the existing technology. Our results are in conformity with this line of thinking.

Table 28. Yield of pearl millet on a total area basis under pond sediment catchment with 0.5 catchment to crop area ratio, and ridge-furrow system of planting without any sealent

Treatment	Yield						
	1970	1973	1975	1976	1977	1978	Pooled over 6 yrs.
	kg/ha						
Pond sediment	2392	2352	2257	1593	1567	1845	2093
Ridge-furrow	3278	3222	2063	2818	2329	1941	2695
Probability level	0 01	0 001	ns	0 001	0.01	ns	0.001

Cost of Harvested Water

Finally we return to answer the question : 'development of a low cost method of sealing the catchment area'.

Rainfall and runoff from pond sediment catchment are available for 1972 to 1975, and again for the seasons 1985 and 1986. For other techniques of water harvesting, such data are available only for the 1985 and 1986 seasons. Hence, the averages of rainfall and runoff for the latter two years were used in calculation of the cost of four sealing materials.

The cost of harvesting water from the systems as we have used must include the unit catchment cost, catchment runoff efficiency, total precipitation, and life of sealent. Table 29 lists the costs of harvesting water for four types of treatment. The unit catchment costs are inclusive of land shaping and compaction in all types of catchments. Application cost is included in pond sediments, janta emulsion, and plastic. Application of 10% solution of gramoxone by rope wick wipe once in a season to kill weeds on pond sediments and compacted earth catchments.

Estimated life of treatments is 5 years for plastic and 10 years for each of janta emulsion, pond sediment, and compacted earth catchment. The total cost spread over the life of treatment, water from plastic and janta emulsion treated system of water harvesting can be obtained for less than 70 cents per 1000 liters, and probably for as little as 0.2 to 3 cents per 1000 liters for the most economical treatments such as compacted earth catchment and pond sediment. However, the runoff efficiencies of plastic and janta emulsion water harvesting systems are 91 to 96%. As a result, they can induce runoff from the low intensity storms which are more prevalent in Indian part of the

Table 29. Water costs for four water harvesting treatments (Rs 12=1 dollar)

Treatment	Initial treatment cost	Average runoff Efficiency	Total water yield from 298 mm rainfall zone, per m^2	Water cost in a 298 mm rainfall zone, per 1000 liter
	$/$m^2$	%	mm	$
Plastic	0.99	96	286.1	3.46
Janta emulsion	1.30	91	271.2	4.79
Pond sediment	0 09	89	265.2	0.34
Compacted earth	0.003	66	196 7	0.02

Thar desert. Apart from this, additional production over economical water harvesting systems will pay off the cost of material in one or two seasons.

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No. 12	The goat in the desert environment, pp. 1-26 (198)	by P.K. Ghosh and M S. Khan
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