Annals of Arid Zone 48(1): 45-50, 2009

Conjunctive Use of Rain and Groundwater in Pearl Millet

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Abstract: Unless affected by a severe drought similar to that of 1987 and 2002, crops in arid Rajasthan usually fail for want of 20 to 25 mm of rain, especially at the fag end of the season. This happened in 2005 cropping season. As there are fertile pockets (oasis), due to the presence of water, scattered over the region, crop failure can be averted by way of groundwater supplementation to precipitation. In 1996, for instance, pearl millet yield was 1725 kg ha^{-1} from rain alone, and when supplemented with 68, 179 and 204 mm of groundwater, crop yields improved to 2466, 3424 and 3615 kg ha^{-1}, respectively. Data for the 1998 season further revealed the significance of rain-groundwater conjunctive use. Combining suboptimal Crop Water Supply (CWS: 256 mm rain + 60 mm groundwater = 316 mm) with optimal fertilizer use (60 kg ha^{-1} N) brought about 2755 kg ha^{-1} of grain. "Bare economic optimum" CWS (353 mm) combined with 90 kg ha^{-1} N tended to move the pearl millet yield curve up to 3010 kg ha^{-1}. A CWS equal to "physiological optimum" (450 mm) in combination with 120 kg ha^{-1} N, envisaged for hi-tech pearl millet production system, resulted in "top profitable yield" at 3750 kg ha^{-1}. Such yield ensures the best use of natural resources as well as external inputs, besides assured food security. To this CWS, 194 mm was supplemented from groundwater. If it were to be used in the rabi season, no winter crop is expected to yield even the "minimum acceptable yield in profitable range". Hence, the use of groundwater in water-responsive pearl millet seems a paying undertaking. As supplement is feasible only by sprinkler system, sprinkler-set renting station in each oasis merits consideration by the state government in order for distribution of social benefits to as many farmers as feasible. Policy-makers are to weigh the feasibility of sprinkler-set renting stations.

Key words: Rainwater, groundwater, nitrogen level, pearl millet, root growth.

Rising demand for food and the social costs of the burgeoning population requires the arid zone agriculture to enhance its productivity, while mounting competition from other sectors for good quality water calls for achieving higher water use efficiency (WUE) to justify the use of water in agriculture. In the arid environment, use efficiency of water is most inefficient (Nelson, 1999), because of large vapor pressure deficit. An increasingly complex quest for improving production and improvements in the rainwater use efficiency (RWUE) brought home the need for conjunctive use of rain and groundwater through sprinkler system.

The question, however, arose on whether as to supplement groundwater with precarious precipitation in a staple crop of pearl millet, or if the limited groundwater should be kept in reserve for sole irrigation in the rainless winter season. The need for improving water allocation vis-à-vis efficiency in arid Rajasthan was very urgent (Andersen, 1996). The International Food Policy Research Institute had also set similar research priorities for the 21st century for water scarce countries.

Rain-groundwater conjunction is a "partial wetting of the root zone" approach – a part of deficit water management. Controversy abounds in the literature as to what level of nitrogen is to be used under sub-optimal supply of water. One school of thought advocated the sub-optimal use of fertilizer in deficit irrigation, while another group of researchers recommended combining optimum fertilizers with sub-optimal irrigation for larger production and WUE (Ram Niwas, 1975; Singh, 1977). This warranted in-depth studies, keeping a wide-ranging combinations of water and nitrogen and demonstration of one or two best options in on-farm programme to enable the farmers to evaluate and opt for the best economic combination of water and nitrogen.

Materials and Methods

A field study was conducted at the Central Arid Zone Research Institute, Jodhpur, during 1996 and 1998. The test crop pearl millet (var. MH

179) was grown in 1996 under optimum management conditions. Line source sprinkler design, less nitrogen levels, was used. The objective was to verify if dimensionless term in earlier established model, Y/YM = 1 - (1-ET/ETm), was unique to crop genotype or could be normalized to a single value that could be used for the past, present and forthcoming crop cultivars.

In 1998, experiment with water and nitrogen variables in two replications was undertaken on the same variety of pearl millet. Ten water regimes ranging from ETm soil water potential in regime 1 to bare minimum in regime 10 within sprinkler system were simulated using the line source sprinkler plot design (Hanks *et al.*, 1976). Five equi-paced nitrogen levels 0, 30, 60, 90 and 120 kg ha^{-1} were arranged at right angle to water variable. An eleventh water regime, beyond the reach of sprinkler, was the rainfed treatment. A few other details are shown in the layout plan (Fig.1).

The system produced a uniform water application pattern along the length of the plot, but uniformly variable across the line of the sprinkler. Rain gauges were kept above the crop canopy in each water regime to measure the simulated rain. All water levels were applied at the same irrigation frequency. The system eliminated the need for border area around each water regime because the incremental change between adjacent treatments was small. Half a meter row length was cut at either end as border since incremental change between adjacent N treatments was large. The system was limited by wind, so water was applied during low wind or calm conditions. Two-metre border on either side, all along the length, was maintained.

Precipitation was used for stand establishment. Rain simulation was monitored by 100% water deficit replacement in ETm plot as soon as the available soil water in 1 m profile was depleted to 50%.

Partial wetting of the root zone during rain simulations in soil water regimes 2 to 10 allowed some storage capacity for precipitation, increasing the contribution of rain to crop water needs, and providing information base to evaluate the significance of conjunctive use of rain with groundwater. The combination of five N levels with 10 soil water regimes helped in determination of the optimum of N (in previous studies 120 kg N ha^{-1} was least limiting to yield) for the desired water regime, ranging from ETm down to bare minimum at regime 10, as also one or two most economic input combinations for demonstration in the on-farm program.

Yield and water-use data recorded from plot 3 (in which N was least limiting to yield and the plot was located in center of the field, free from advection) in 1 to 10 water regimes within sprinkler pattern were utilized to determine yield to water-use relationship.

Frequency of irrigation remained the same for all soil water regimes from 1 to 10. In regime 1, soil water in 1 m profile was charged to field capacity each time to satisfy ETm to attain Ym. Soil water deficit replacement descended linearly from 100% in regime 1 to bare minimum in regime 10, and therefore, at levels 2 to 10 no irrigation restored the soil water to field capacity. This experiment thus also amalgamated the study on partial wetting of the root zone approach that looked for preplant irrigation to charge the soil profile to field capacity, and high frequency growing season irrigation as proposed to attain ETm and Ym.

Thus the experiments combined several studies that might be needed to determine (1) the economic yield to water-use relationship, quantifying as well the ETm, Ym and value needed to develop a generalized yield prediction model, (2) significance of conjunctive use of rain with groundwater, (3) partial wetting of the root zone, (4) optimal allocation of water, and (5) optimal irrigation programing. Crop Water Supply, CWS [CWS = (soil water at planting + effective rain + rain simulated) – (residual water at harvest)] was worked out to relate it to the crop yield.

Results and Discussion

CWS to yield relation

CWS versus yield relationship was linear with coefficient of determination at 1.0, typical of a very high relationship. There are several options to integrate rainfall and groundwater (Table 1), bearing in mind the desired water-use efficiency.

Integrated use of rainfall-groundwater in pearl millet production system was sustainable considering a little over 4 t ha^{-1} root biomass to 1 m profile (Table 2). Crop yield efficiency (CYE) offers grain yield anticipation from stalk biomass sampled immediately before ear emergence.

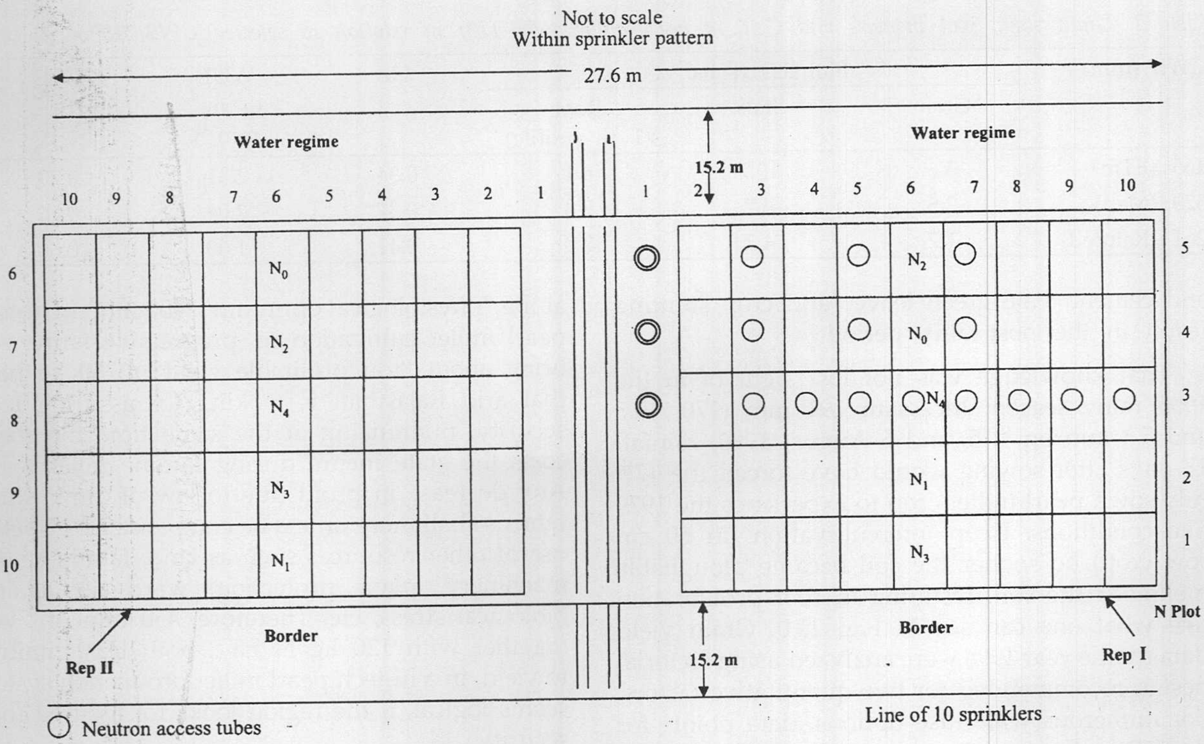


Fig. 1. Line source sprinkler design.

A new hypothesis

Usually the soil-water at 15 atm has been the lower limit to plant-available-water. The first disagreement to this hypothesis was observed from soil water depletion monitored in sprinkler- irrigated 'sewan' (*Lasiurus sindicus*) during 1985, the year of grass establishment. During March to June, when evaporative demand was high, the soil had depleted -11 to -4 mm of available soil water without any wilting symptoms (Singh *et al*., 1990). Being a desert grass, it was thought that this species could deplete the soil moisture below 15 atm level at which a crop might succumb.

Soil water depletion monitored in MH-179 pearl millet in 1996 had shown that crop would also deplete the soil water below 15 atm level. The two observations conclusively proved that at least on a loamy sand soil of arid Rajasthan, 15 atm moisture was not the lower limit (Table 3). Drought resistant pearl millet crop could deplete soil water below the commonly determined wilting coefficient, thriving on upward soil water movement in the vapor phase along the thermal gradient during cool nights in the desert.

New dimension in crop root growth

If the soil water supply remains adequate (ETm plot), roots, like shoots, grow in the direction of least interference. Indication to such root growth pattern was observed for the first time in the late -1970s in tomatoes planted in triple row under the drip irrigation system, and once again in the 1996 study on MH 179 pearl millet (**Fig. 2a**). In the latter, pool of water-fertilizer-intercultivation promoted horizontal and vertical root proliferation, which were vital for better uptake of water and nutrients from entire soil profile and resistance to drought.

Low Water Supply (LWS) or rainfed conditions restricted root development to surface layer – an adjustment to tap more rainwater (Fig. 2b), especially light rains.

Following heavy successive rains, as experienced in 1979, loamy sand soil has a tendency to seal

Table 1. Yield of pearl millet (MH 179) versus CWS, 1996

Yield (kg ha^{-1})	CWS (mm)					
	261	279	329	394	440	465
Grain	1725	2231	2466	2958	3424	3615
Stalk	4176	6376	6716	8586	10076	10740

Table 2. Grain stalk, root biomass and CYE of pearl millet (MH-179) in relation to selected CWS, 1996

CWS (mm)	Biomass (t ha^{-1})			HI	WUE (g m^{-2} mm^{-1})	CYE
	Grain	Stalk	Root (1 m profile)			
465 (ETm)	3.6	10.7	4.1	0.34	2.31	0.79
329 (Med)	2.5	6.7	3.8	0.37	2.04	0.76
261 (Rainfed)	1.7	4.2	2.0	0.41	1.60	0.66

and cement. Pale green leaves and crop stunting result in the post-rainy period.

That knowledge was not lost sight of in the 1996 rainy season. Incessant 191 mm (170, 15.5 and 5.5 mm on 4, 5, and 6 August 1996) rainfall 18 days after sowing would have forced the 17th July sown pearl millet crop to experience the 1979 like conditions. Deep intercultivation (in 60 cm row crop) no sooner the soil became ploughable mellowed the soil, resulting in root proliferation like what one can see in Fig. 2a,b. Grain yield data for the year 1998 were analyzed using factorial design recommended for two quantitative factors. For numerous water-use options, data points for the ETm plot and that for the rainfed treatment and three water regimes in between were selected (Table 4).

Mid-point CWS lying between rainfed and ETm plots was 353 mm. This value was considered the "bare economic level", where a rupee gain would equal the last rupee spent on the input. A value below this point was considered the "sub-optimal level". The one for the ETm plot naturally was the "physiological optimum". Under optimum crop management, CWS at this rate is anticipated to result in "top profitable yield".

Among the five water-use options, combining sub-optimal CWS (316 mm) with the optimal fertilizer use (60 kg N ha^{-1} mid-point) resulted in a yield of 2755 kg ha^{-1}. This yield level was significantly superior to 1679 kg ha^{-1} yield obtained from the use of the same water supply combined with sub-optimal fertilizer N (30 kg ha^{-1}). This finding did not support the practice of using sub-optimum dose of fertilizer in a crop receiving sub-optimal CWS.

At the bare economic CWS (353 mm), if a farmer can afford improving 30 kg ha^{-1} N to 90 kg ha^{-1}, pearl millet yield curve moves up to 3010 kg ha^{-1}. This action offers tremendous food security, besides being economical.

Liebscher's law of optimum links low yield with low efficiency of resource use. Application of CWS at the "physiological optimum" (450 mm) in hi-tech pearl millet cultivation on progressive farms will bring about "top profitable yield" (3750 kg ha^{-1}) that arid Rajasthan is looking for assuring food security, minimizing at the same time the social costs the state incurs during famine relief work. Any decrease in profit due to law of diminishing returns shall more or less be compensated by better use of other resources such as land, family labors, machinery, plant protection, ward off against biological stress, etc. Therefore, 450 mm of CWS, together with 120 kg N ha^{-1}, both least limiting to yield, in a hi-tech pearl millet production system seems logical, if the region looks for assured food security.

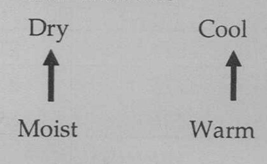
Alternatively, the farmers may use declining groundwater conjunctively with precarious rainwater in the pearl millet production system, or leave it in reserve for use in the ensuing winter season during which no rain falls. Data in Table 4 show the maximum rain simulated 194 mm in the ETm plot. Partial wetting of the potential root zone approach, an important component of deficit irrigation, is by far the best to make better

Table 3. Soil moisture (mm) in pearl millet (MH 179). Last 2.5 mm rain on 10 September 1996

Date	Soil depth (cm)	
	0-20	0-100
September 10	6.4	50.1
September 16	5.5	43.9
September 21	4.9	41.0
September 27	4.5	36.3
October 5	4.1	36.0
October 8	4.1	35.1
October 9	4.0	34.1

15 atm moisture: 9 mm in 20 cm; 45 mm in 100 cm

Soil horizons differeing to temperature and moisture



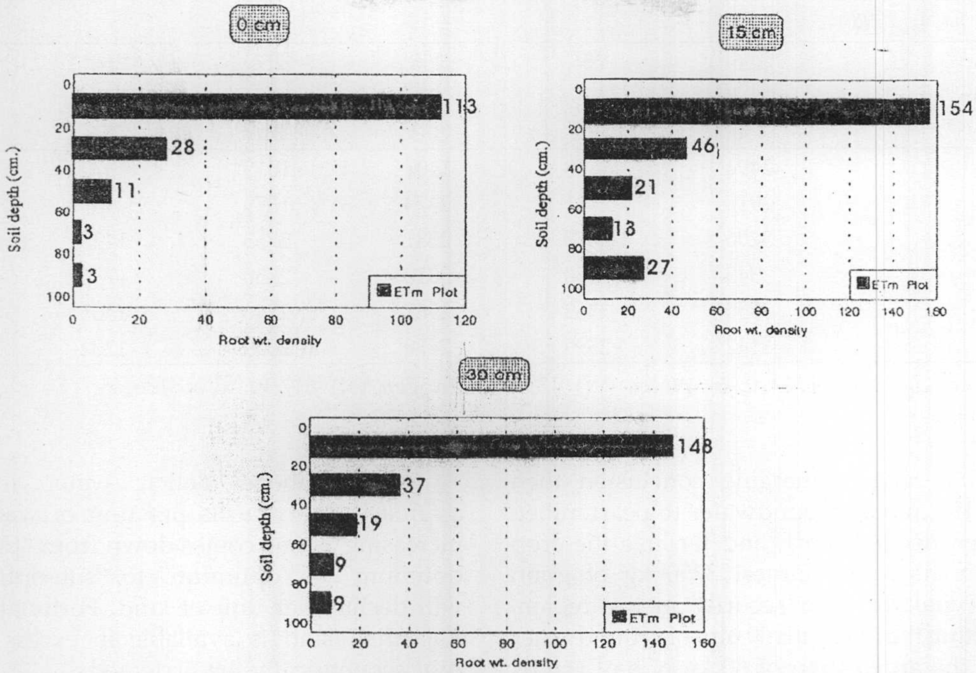


Fig. 2a. Root weight (wt.) density (g x 10^{-5} cm^{-3}) of soil volume at 0, 15 and 30 cm distance form row (rows 60 cm apart) in ETm plot.

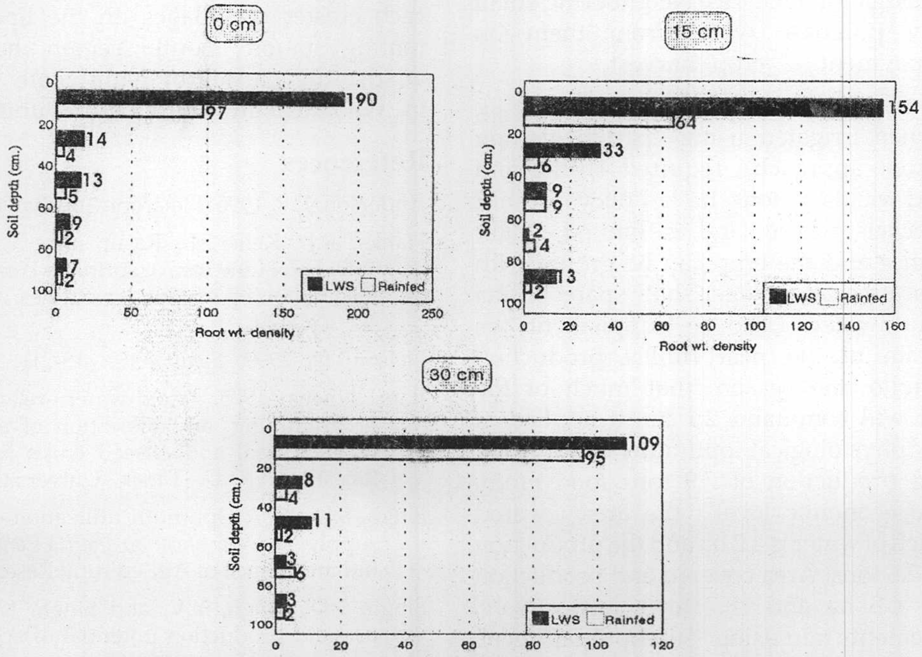


Fig. 2b. Root wt. density per cubic cm at 0, 15 and 30 cm distance from row (rows 60 cm apart).

use of this limited water in a winter crop. However, yield reduction was noticed when the soil profile to one meter depth was not charged to field capacity initially. To this depth, 156 mm pre-plant irrigation thus became essential. No winter crop at the seasonal irrigation with remainder 38 mm (194 mm – 156 mm = 38 mm) can be expected to produce even the minimum acceptable yield in

Table 4. Interactive influence of crop water supply (CWS, mm) and five N rates (kg ha^{-1}) on pearl millet yield (kg ha^{-1}), 1998

N							
	Rain	256	256	256	256	256*	Mean
	Rain simulated	194	109	97	60	0	
	CWS	450	365	353	316	256	
0		2494	1678	1401	1019	370	1717
30		2917	2431	2373	1679	963	2278
60		3206	2477	2581	2755	1435	2594
90		3345	3050	3010	2350	1736	2877
120		3750	3362	2987	2246	1505	3010
Mean		3142	2599	2470	2009	1202	

* Normal rain 248 mm; LSD 0.05: Water (W) 45 kg, Nitrogen (N) 61, W x N 136 kg.

the profitable range. Emerging conclusion then is to apply 194 mm of groundwater to pearl millet, as and when needed most, and fertilize the crop at 120 kg N ha^{-1} and harvest 3750 kg of grain per ha, so vital for food security in the region. Supplementing the rain with 60 mm of groundwater along with the application of 60 kg N ha^{-1} stands within the reach of small farmers. In arid Rajasthan, energisation of tubewells or even dugwells are fairly expensive, and so, large farmers by and large posses irrigation facilities. Neighboring small farmers may purchase water from them on contractual payment at crop harvest.

A wheat crop receiving 120 kg N plus 40 kg P_2O_5 ha^{-1} when irrigated using "partial wetting of the root zone approach", required 410 ha mm of water and yields 6 tons ha^{-1}. Policy to shift wheat to pockets where land is limited, water is in abundance and the crop can be grown with better comparative advantage, shall spare 410-ha mm of groundwater. Used to supplement the precarious rain in the pearl millet production system the following season, that much of the groundwater will command 2.1 ha, if applied at the rate of "physiological optimum" and bring about a total production of 7.9 tons food grain. At the "bare economic level", the area covered from that much of water is 4.2 ha and the production achieved is 12.6 tons. Area covered and production obtained are 6.8 ha and 18.7 tons, respectively, as one supplements rain using "sub-optimal" level.

In the above deficit water management approach, the returns per unit of water goes on increasing as one comes down from "physiological optimum" to "optimum" to "sub-optimum", but will decline per unit of land. Fortunately, in arid Rajasthan land is available in excess than what can economically be irrigated.

For implementation of our suggestions, state agriculture department may work out feasibility of establishing "sprinkler set" renting station in each cluster of villages on the line of "machine renting station" South Yemen, had established amidst the cluster of eight State Farms located in Wadi Tuban Delta before unification,.

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