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Monitoring of Productivity and Crop Water Stress in Pearl millet using the SPAW Model

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Abstract: For assessment of soil water in the Indian arid zone, the profile soil moisture content in pearl millet, grown under optimum moisture and rainfed conditions at Jodhpur, was simulated using the SPAW (Soil-Plant-Air-Water) model for seven cropping seasons during 1990 to 1996. The simulated profile soil moisture content was close to the observed data, both under optimum moisture and rainfed crop conditions, as well as when crop was sown under late (1992), early (1993) and normal (1994) conditions, with RMSE (root mean square error) values ranging between 0.62 and 1.83. The Water Stress Index (WSI), calculated using the SPAW model, had a linear, but inverse relationship with the productivity of pearl millet (Y, kg ha^{-1}). The regression equation between them was Y= -258.9 WSI + 3847.2 (R^2=0.94) and was useful for pearl millet yield estimation in the Indian arid region.

Key words: Water Stress Index, pearl millet, grain yield, SPAW model, arid region.

Pearl millet (*Pennisetum glaucum* L.) is the predominant crop of the arid tropics in India and Africa. Estimation of productivity of pearl millet, through soil moisture monitoring, helps in planning food grain availability and distribution. In the hot arid regions of India, the average daily solar radiation is as high as 21.4 MJ m^{-2} and the solar radiation conversion efficiency is mainly influenced by water and nutrient availability (Monteith, 1977). Pearl millet is susceptible to drought stress during flowering and grain filling stages, reducing grain yield at a smaller rate in dwarf hybrids than in tall varieties (Mahalakshmi *et al.*, 1987, 1988, 1991). The productivity of pearl millet in arid zones is low (470-530 kg ha^{-1}) due to low and erratic rainfall and poor soil fertility. The grain yield data of past 19 years in Jodhpur region showed a decreasing trend in the productivity of rainfed pearl millet (Rao and Saxton, 1995). The present investigation was, therefore, aimed at assessing the pearl millet production levels at different moisture availability situations using the Soil-Plant-Air-Water (SPAW) model simulations.

Materials and Methods

Pearl millet (cv. MH 179) was grown under optimum moisture and rainfed conditions at the Central Arid Zone Research Institute, Jodhpur (26° 30′ N, 73° 10′E; 224 m above MSL), for seven consecutive seasons. The seasonal rainfall was 767, 183, 179, 226, 489, 262 and 387 mm during 1990 to 1996. Soil of the location is loamy sand (hyperthermic, Haplocambids) having textural composition of 83% sand, 9% silt and 8% clay. The bulk density is 1.55 g cm^{-3} and infiltration rate 15.1 cm h^{-1}.

Table 1. Time taken (julian days) for completion of various phenophases of pearl millet

Crop stage	Optimum moisture						Rainfed					
	1992 late	S.D.	1993 early	S.D.	1994 normal	S.D.	1992 late	S.D.	1993 early	S.D.	1994 normal	S.D.
Sowing	209		179		185	0.75	209		179		185	
Germination	210	0.75	180	0.75	186	0.53	210	0.76	180	0.76	186	0.76
Emergence	212	0.92	182	0.75	189	1.41	212	1.31	182	0.93	189	0.75
End of juvenile period	217	0.75	187	0.75	193	0.75	217	1.60	187	1.07	193	1.19
Tillering	230	0.75	201	1.19	202	0.75	230	1.19	201	1.07	202	0.75
End of leaf growth	251	1.31	235	0.75	202	0.75	251	1.19	218	0.93	210	0.75
Ear emergence	263	1.60	236	1.19	225	1.19	263	1.19	231	1.19	224	1.19
Anthesis	267	0.92	241	0.75	236	0.75	267	1.09	246	0.75	235	0.75
Physiological maturity	294	1.19	272	0.75	277	1.19	276	1.19	275	0.75	275	1.19

S.D. = Standard deviation.

The soil has moisture retention of 0.102 m^3 m^{-3} at -0.1 bar and 0.26 m^3 m^{-3} at -15 bar. The soil is low in organic carbon content (0.09-0.20%), poor in nitrogen (0.03%), medium in available phosphorus (12-18 kg ha^{-1}) and potassium (220 kg ha^{-1}).

Main plots (100 m^2 size) for optimum moisture and rainfed situation were used for recording phenology, grain and biomass yields of pearl millet. The main plot was divided into 8 sub-plots and each was taken as replication of the treatment. Three plants in each replication (sub-plots) were tagged for recording phenology and plant growth parameters. The mean of the 3 samples from each of 8 replications were used for calculation of standard deviation of sample. The grain, stover and total biomass yields were recorded for each of the sub-plots (replications) and were used for calculation of standard deviation of population. Application of 40 kg N ha^{-1} was made to the crop under both optimum moisture and rainfed situations. The optimum moisture in the profile was maintained by giving surface irrigation whenever the 90-100 cm profile moisture depleted to 50% of available soil moisture. There were 5 to 8 irrigations, each of 62.7 mm depth, given during the cropping season to maintain moisture level above 50% of available water capacity (AWC).

Soil moisture in each of the depths of 0-20, 20-40, 40-60 and 60-80 cm was the mean of eight replications recorded in both the optimum moisture and rainfed crop conditions on alternate days, using a pre-calibrated neutron soil moisture meter (Troxler 4300). The mean soil moisture contents were compared with the estimated values using the SPAW model. The root mean square error (RMSE) between the observed and the estimated soil moisture contents were calculated pooling all data separately for each season and layer, and

Table 2. Yield and yield attributes of pearl millet

Crop character	Optimum moisture						Rainfed					
	1992 late	S.D.	1993 early	S.D.	1994 normal	S.D.	1992 late	S.D.	1993 early	S.D.	1994 normal	S.D.
No. of plants (m^{-2})	15.3	0.24	15.3	0.25	16.1	0.30	15.1	0.17	12.5	0.16	15.8	0.29
No. of tillers (m^{-2})	53.1	0.62	57.6	0.54	44.3	0.39	46.4	0.54	36.9	0.41	35.5	0.46
Grain weight (g $plant^{-1}$)	21.7	0.43	23.7	0.41	24.2	0.45	7.4	0.42	6.7	0.46	13.6	0.35
No. of heads (m^{-2})	37.9	0.25	24.6	0.40	21.3	0.56	26.8	0.21	13.0	0.37	15.2	0.21
No. of grains $head^{-1}$	2131	3.12	49324	3.85	3041	3.02	1239	1.77	14048	4.03	1914	3.85
1000 grain weight (g)	19.6	0.35	16.1	0.42	17.7	0.33	11.9	0.38	11.4	0.55	15.7	0.33
Head length (cm)	24.2	0.62	26.9	0.67	24.7	0.39	20.1	0.56	18.6	0.69	22.2	0.56
Grain weight (kg ha^{-1})	3368	3.46	4292	3.96	3700	2.34	1573	7.12	832	3.39	2638	2.87
Stover weight (kg ha^{-1})	6326	3.39	8819	2.45	8076	2.55	4011	2.24	1909	3.57	5413	2.95
Total dry matter (kg ha^{-1})	9694	2.55	13111	3.27	11776	3.67	5584	3.67	2741	2.74	8051	1.80

S.D. = Standard deviation.

for each of the rainfed and optimum moisture crop situation. Soil depth in the study area varied from 90 cm to 100 cm, below which a hard pan exists, restricting the vertical drainage.

Profile soil water balance in the 80 cm soil depth, and the water stress index under pearl millet crop, were computed using the SPAW model (Saxton *et al.,* 1974, 1992; Saxton, 1989; Rao and Saxton, 1995). The rainfall and class A pan evaporation used in the model were obtained from a nearby meteorological observatory located 50 m away from the experimental plots. The class A pan evaporation was adjusted with a pan coefficient of 0.75 to 0.85 (Doorenbos and Pruitt, 1977) before they were used as potential evapotranspiration (ET). From the potential ET, the model determined the actual ET from calculation of interception evaporation, soil water evaporation and plant transpiration. Soil water evaporation and potential transpiration were partitioned from the potential ET, based on the canopy shading percentage. The potential transpiration was then adjusted to obtain actual transpiration with coefficients for root density in each layer at different crop stages and the relationship between transpiration and available soil water content curves (Denmead and Shaw, 1962).

Leaf area and root density at different crop stages were recorded for inputting in the model. It was assumed that the upper boundary layer (2.5 cm) had no roots and that water in this layer readily evaporated at potential rate. An upper limit of 2.5 mm was assumed for rainfall interception loss. After the daily infiltration, less the water lost through actual ET, the available water was redistributed among the soil layers and segregated into runoff and deep percolation. Upward water movement for evaporation was estimated by the Darcian method and the runoff using the modified Soil Conservation Service (SCS) curve number method (Saxton, 1989). Daily accumulated water stress index (WSI) for assessment of grain yields, for each of the season, was computed as:

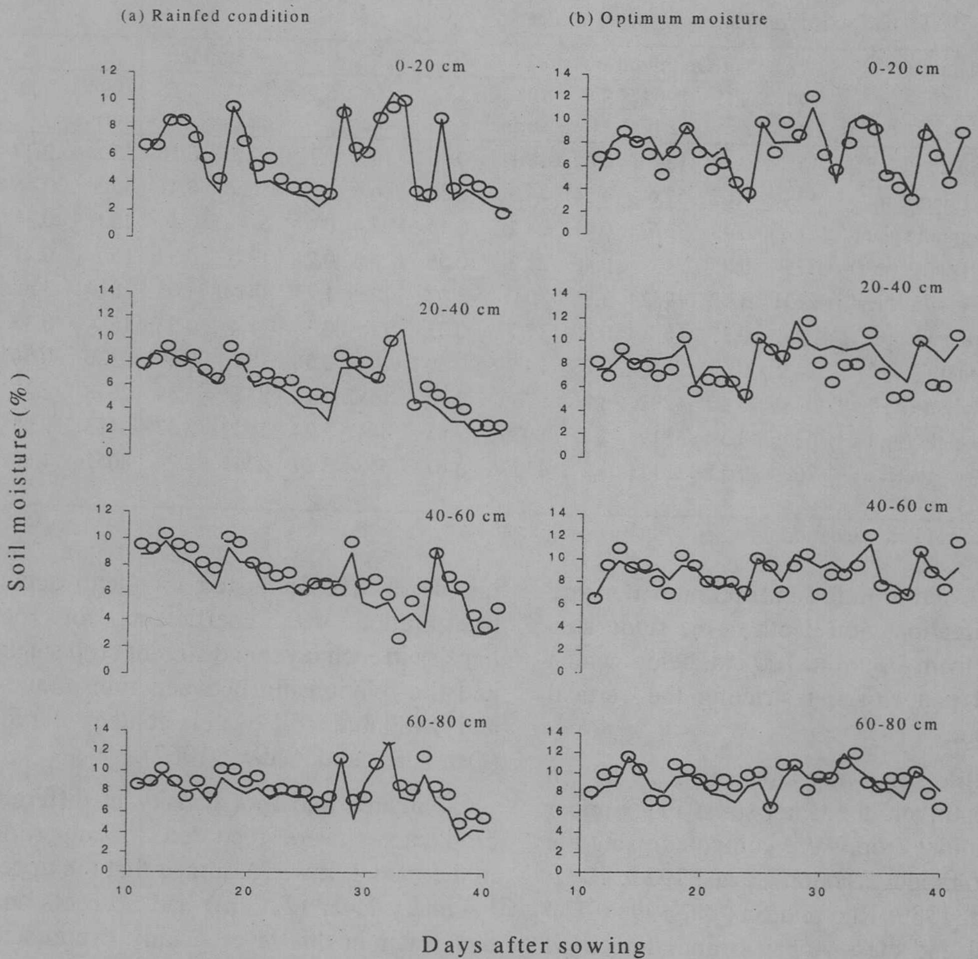

Fig. 1. Soil moisture under late sown pearl millet (1992).

$$\sum_{Planting}^{Harvest} 1-(T/T_p)\ X\ SUS$$

where, T and T_p are actual and potential transpiration (mm day^{-1}) computed using the model, and SUS is the seasonally dependent weighting factor for grain yield susceptibility (Sudar *et al.*, 1981; De Jong and Zentner, 1985). The grain yield susceptibility values for pearl millet used in the model were based on the experiments of Mahalakshmi *et al.* (1987, 1988, 1991).

Results and Discussion

Crop phenology, growth and yield characteristics

The time taken for completion of different phenological stages and yield attributes of pearl millet sown under late (1992), early (1993) and normal (1994)

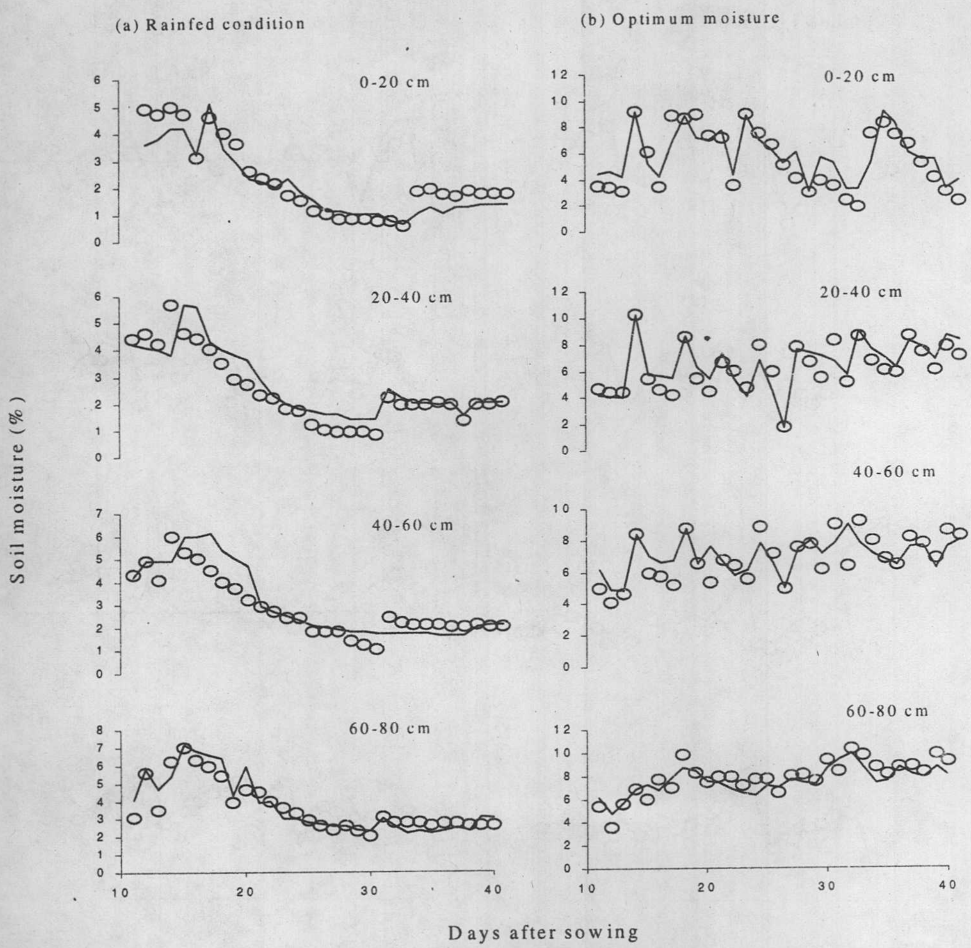

Fig. 2. Soil moisture under early sown pearl millet (1993).

onset of monsoon are presented in Tables 1 and 2, respectively. Crop maintained under optimum moisture and rainfed conditions took similar time to reach end of juvenile period. The stages like tillering, end of leaf growth, ear emergence, anthesis and physiological maturity took 2 to 5 days more under optimum moisture condition than under rainfed condition (Table 1). Rainfed crop matured in 67 days under delayed sowing, in 96 days with early, and in 90 days under normal sowing condition. The variation in maturity of optimum-moisture-crop was between 85 and 92 days (Table 1). The initial set plant population of 20 plants m^{-2}, under rainfed condition, declined to 14 to 16 plants m^{-2} due to prevailing water stress conditions.

The optimum-moisture-crop yielded 3787 kg ha^{-1} compared with 1681 kg ha^{-1} by the rainfed crop (Table 2). The mean biomass production of optimum moisture

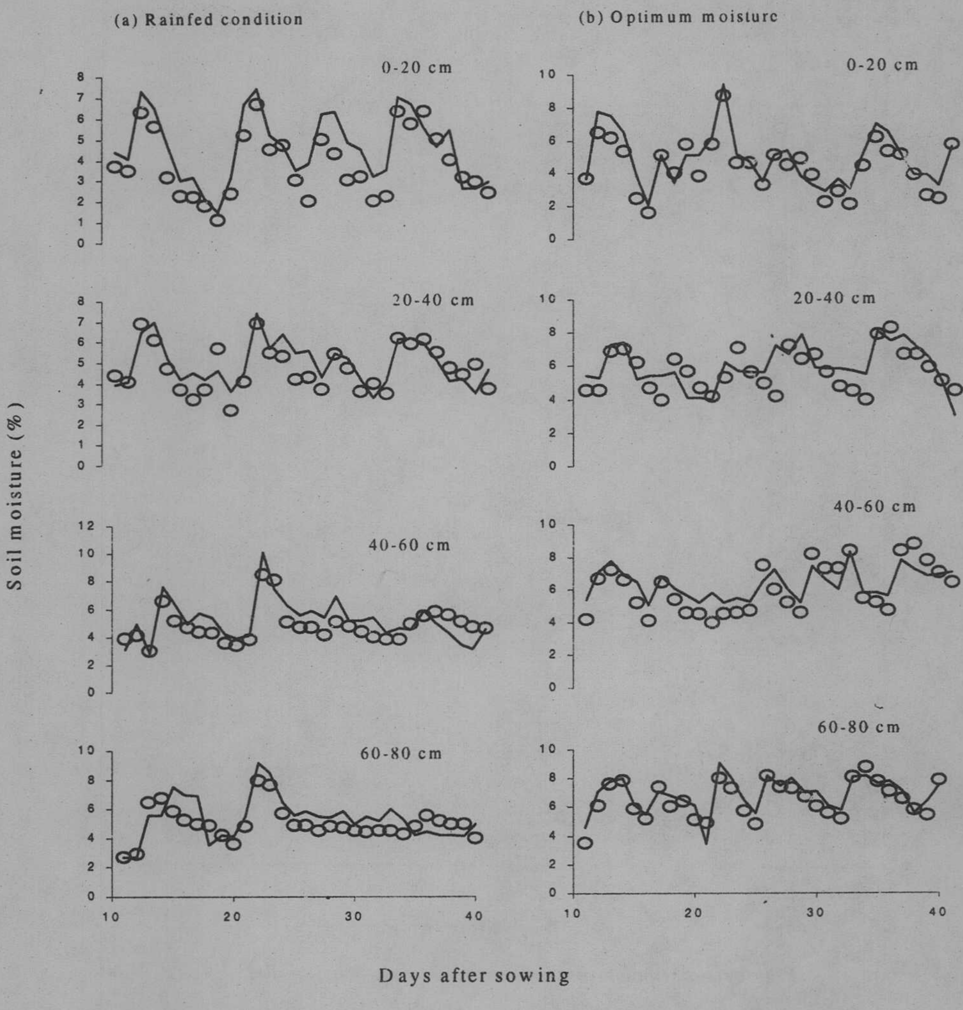

Fig. 3. Soil moisture under normal sown pearl millet (1994).

crop was 7740 kg ha^{-1} compared with 3775 kg ha^{-1} from rainfed crop. The grain yield of optimum-moisture-crop was influenced more by the increase in number of tillers/heads and grain weight. The additional contribution of tillers towards grain weight was significant under optimum- moisture condition (2904 kg ha^{-1}) as compared with the rainfed crop (1232 kg ha^{-1}).

The grain yields of rainfed pearl millet were 832 kg ha^{-1} under early (1993), 1573 kg ha^{-1} under late (1992) and 2638 kg ha^{-1} under normal (1994) dates of onset of rains in the area (Table 2).

Estimation of soil moisture

The discussion on the comparison of estimated and observed soil water is

Table 3. Root mean square error (RMSE) between the observed and the simulated soil moisture contents

Year	Soil depth (cm)	Mean soil moisture content (%) during the cropping season		RMSE
		Observed	Simulated	
Under optimum moisture crop				
1992	0-20	4.9	4.2	1.49
	20-40	6.1	4.7	1.51
	40-60	6.9	5.9	1.44
	60-80	7.9	6.7	1.,83
1993	0-20	2.3	2.2	0.95
	20-40	2.3	2.5	0.75
	40-60	2.5	2.9	0.75
	60-80	3.2	3.3	0.62
1994	0-20	3.3	4.2	1.22
	20-40	4.3	4.6	1.42
	40-60	4.5	4.8	1.26
	60-80	4.8	5.1	1.14
Under rainfed crop				
1992	0-20	6.9	7.2	1.54
	20-40	7.8	8.3	1.77
	40-60	8.9	8.7	1.34
	60-80	9.5	8.9	1.50
1993	0-20	5.1	5.3	1.22
	20-40	6.4	6.1	1.05
	40-60	6.9	6.8	1.24
	60-80	8.0	7.4	1.04
1994	0-20	4.2	4.8	1.04
	20-40	5.7	6.1	0.95
	40-60	6.9	6.9	0.87
	60-80	6.6	7.2	0.94

confined to the situations with the onset of south-west monsoon under late condition in 1992, early in 1993 and normal in 1994, providing assessment at three sowing dates viz., late, early and normal, respectively, (Figs. 1a to 3b).

The scatter between the observed and the simulated soil moisture content was relatively high under the late sown (1992) condition of pearl millet (Fig. 1a & b). During this period, the simulated soil moisture, in general, was lower than the recorded soil moisture under rainfed crop condition, whereas it was higher than the observed one under optimum moisture condition. The RMSE values for 1992 were between 1.44 and 1.83 under rainfed crop, and between 1.34 and 1.77 under optimum-moisture crop (Table 3). During dry periods, estimated soil moisture contents under rainfed crop were slightly lower and

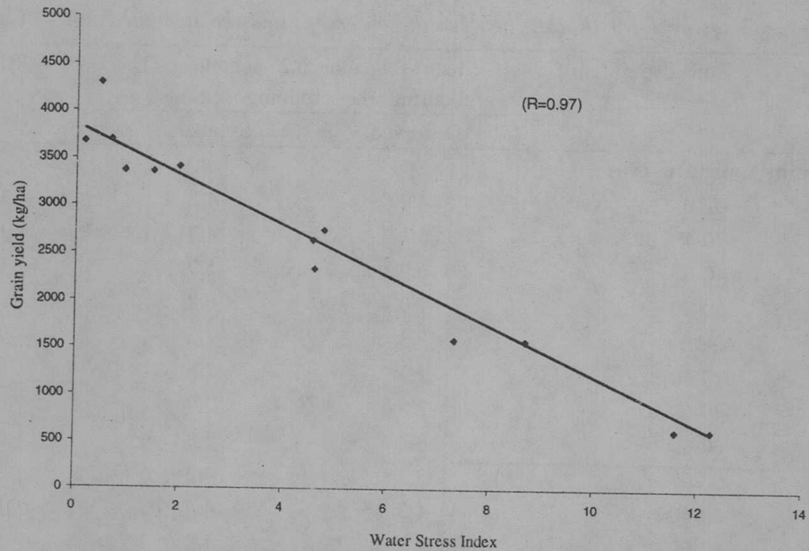

Fig. 4. Relationship between water stress index and grain yield of pearl millet.

whenever the monsoon revived, the estimates were slightly higher than the measured values. Such variations were also observed under the optimum-moisture-crop due to irrigation. Under optimum-moisture-crop, the simulated values were much closer (within 2.0%) to the observed soil moisture content.

A much closer relationship between measured and estimated soil moisture was observed during 1993 (early sown) under both optimum moisture and rainfed crop conditions (Figs. 2a & b). The RMSE values were between 1.04 and 1.22 under optimum moisture, and between 0.62 and 0.95 under rainfed crop condition. Rainfed crop received about 120 mm of rainfall during July 18-20, which helped the crop for good establishment, but later, there was a break for 52 days till September 3. During this long dry spell, the estimated depletion of soil moisture content through the model established a closer relationship with the observed moisture content.

Table 4. Soil water balance (mm) under rainfed pearl millet

Parameter	1990	1991	1992	1993	1994	1995	1996
Rainfall	767	183	179	226	489	262	387
Potential evapotranspiration	604	480	379	566	519	422	519
Actual evapotranspiration	249	184	174	195	301	192	270
Soil evaporation	116	70	65	110	160	78	104
Transpiration	133	114	109	85	141	114	166
Interception	58	35	14	10	29	32	39
Runoff	302	3	0	19	85	52	46
Percolation	173	13	9	12	69	56	110

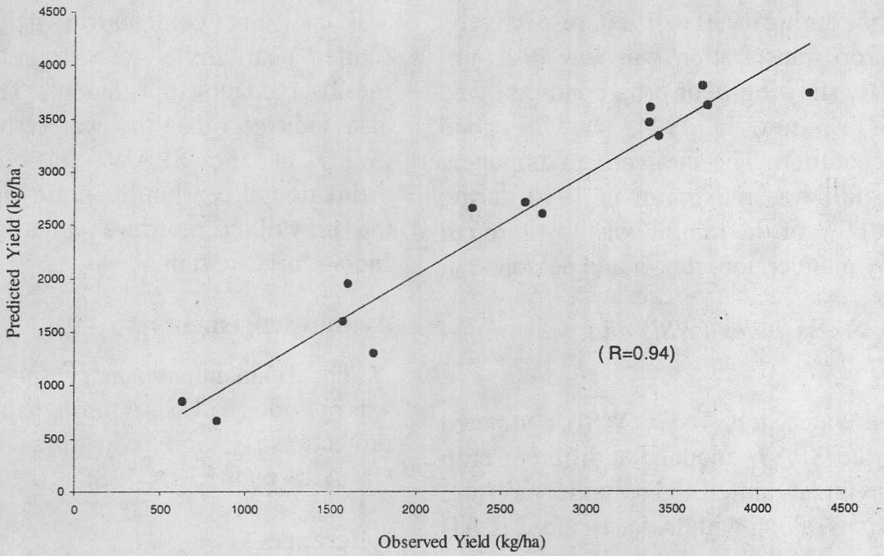

Fig. 5. Predicted and observed pearl millet yield using the SPAW model.

During 1994 (normal sown), both under optimum moisture and rainfed pearl millet, the soil moisture contents were high due to prevailing high rainfall conditions (Figs. 3a & b). The RMSE values were between 0.87 and 1.04 under optimum moisture, and between 1.14 and 1.42 under rainfed crop condition.

Soil water balance (mm) under pearl millet

The soil water balance parameters computed using the SPAW model under rainfed pearl millet are presented in Table 4. Rainfall during the cropping season varied from 179 mm in 1992 to 767 mm in 1990. The estimated crop evapotranspiration (ET)

Table 5. Water stress index (WSI) and pearl millet performance

Year	Optimum moisture					Rainfed				
	WSI	LAI	Observed grain yield (kg ha^{-1})	S.D.	Predicted grain yield (kg ha^{-1})	WSI	LAI	Observed grain yield (kg ha^{-1})	S.D.	Predicted grain yield (kg ha^{-1})
1990	1.48	4.23	3360	4.71	3464	4.61	2.93	2330	10.43	2653
1991	4.79	4.49	2740	18.25	2606	11.58	2.01	629	10.35	848
1992	0.94	5.78	3368	3.46	3603	8.68	2.92	1573	7.12	1599
1993	0.45	6.07	4292	3.97	3730	12.27	2.02	832	3.39	669
1994	0.87	5.96	3700	2.35	3622	4.37	3.30	2638	2.87	2715
1995	1.99	3.18	3416	8.47	3331	9.84	2.43	1751	13.04	1298
1996	0.16	4.79	3673	8.00	3805	7.32	2.17	1599	13.23	1951

WSI = Water stress index, LAI = Leaf area index, S.D. = Standard deviation.

was 249, 184, 174, 195, 301, 192 and 270 mm during 1990 to 1996, respectively. The crop transpiration was low (70 mm) in 1991, showing poor crop condition, and high (112 mm) in 1994, showing good crop condition. The ineffective component of rainfall was maximum in 1990 during which 69% of the rainfall was lost through canopy interception, runoff and percolation.

Water Stress Index (WSI) and pearl millet performance

The Water Stress Index (WSI), computed using the SPAW model for different crop seasons under rainfed and optimum moisture conditions, along with leaf area index (LAI) and grain yield of pearl millet, are presented in Table 5. In rainfed crop, when the WSI values were low (4.37) in 1994, the LAI and grain yields were high. When the WSI was high (12.27) in 1993, the LAI and grain yields were low. Thus, with the increase in the seasonal WSI value, there was a decrease in the LAI and grain yield, showing higher crop water stress. The regression relationship between WSI and pearl millet grain yield (Y, kg ha^{-1}) recorded from experimental fields is revised and shown in Fig. 4. The modified regression equation, viz., Y = -258.9 WSI + 3847.3 (R^2 = 0.94) predicted pearl millet grain yields, both under optimum moisture and rainfed conditions, closer to the recorded yields (Fig. 5).

Conclusions

Pearl millet, which is an important cereal crop of arid tropics, is very much influenced by soil moisture deficits created by low and erratic nature of rainfall. Simulated soil moisture contents in irrigated and rainfed pearl millet were found closer to the observed moisture contents. The analysis also indicated that the water stress index (WSI) of the SPAW was useful for estimation of pearl millet grain yields under the prevailing moisture situations in the Indian arid region.

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