Evapotranspiration and soil moisture balance in relation to yield of pearl millet (*Pennisetum glaucum*)

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सार — हिसार और बेल्लारी के कृषि मौसम विज्ञानिक आंकड़ों के उपयोग द्वारा बाजरे की फसल तैयार होने के दौरान विभिन्न अवस्थाओं में पौधे के लिए वाष्पोत्सर्जन की आवश्यकता की जाँच की गई है। फसल के लिए जल की आवश्यकता का पता लगाया गया है तथा इसके बारे में विस्तार से बताया गया है। फसल प्रतिबल स्थिति का मूल्यांकन करने के लिए समय-समय पर मिट्टी में पाई जाने वाली नमी की घट-बढ़ का आकलन किया गया है। फसल की वृद्धि के दौरान इसमें पाई जाने वाली नमी का मूल्यांकन तथा पैदावार के आकलन का भी प्रयास किया गया है।

इस अध्ययन से ज्ञात हुआ है कि दोनों स्थानों पर बाजरे के पौधों में फूल आने के समय उसे जल की आवश्यकता सबसे अधिक होती है। बाजरे की समान किस्म के लिए बेल्लारी की तुलना में हिसार में फसल के लिए जल की आपूर्ति अधिक सुगमता से होती है। मृदा नमी संतुलन तकनीक पर तैयार की गई उपज तालिका से पैदावार का सही ढंग से आकलन किया जा सकता है।

ABSTRACT. In this study, the agrometeorological data of Hisar and Bellary have been utilized to examine evapotranspirative demand of the pearl millet at different phases during the crop growing period. Water use efficiency of the crop has also been worked out and discussed. Cumulative soil moisture balance was computed to assess the crop stress situation. Attempt has also been made to assess the moisture availability to the crop during the growing period and to estimate the yield.

The study revealed that the pearl millet used maximum amount of water during the flowering stage at both locations. The same variety of pearl millet was found to use water more efficiently at Hisar than at Bellary. The yield index based on soil moisture balance technique was found to give a good indication of the yield.

Key words — Evapotranspiration, Yield index, Water use efficiency (WUE).

1. Introduction

Pearl millet is a staple food for most of people in peninsular and northwest India. The crop is cultivated for grains as well as fodder in the arid regions of Asia and Africa and as a pasture in USA. In India it occupies 12 million hectare representing nearly 30% of the acrage and 11% of total cereal production (I.C.A.R. 1987). The yield is above 750 kg/ha, though low, widely fluctuates from year-to-year due to variations in the rainfall. Since most of the water consumed by this crop is taken up from the available water in the soil, the period of available water to the crop is determined by the soil moisture conditions as well as by the water balance (precipitation minus evapotranspiration). In order to estimate the soil moisture, not only the climatic variations, but also the parameters of the edaphic environment, such as the position of the field in the landscape, the soil texture etc. should be taken into account. The crop characteristics also plays important role. Crops producing a high leaf area index will normally transpire at higher rates, and therefore, consume more water. The yield is generally dependent on the available soil moisture between the limits of field capacity and some critical range of soil moisture which is higher than the wilting point. The moisture absorbed at levels below wilting point is not effective in maintaining vegetative growth and affects the yield and quality of the grain. Therefore, in considering the amount of water available to this crop, the wilting point is of little significance as the lower limit of soil moisture. The lower limit of moisture is of little significance as the lower limit of soil moisture availability depends on the species involved and on the prevailing weather conditions.

One of the advantages of the soil moisture balance, is that it helps to estimate the extent to which the water need of a crop is met at any stage of its development and growth. Recent soil moisture and evapotranspiration studies have confirmed the usefulness of water balance technique (Gupta 1980, Seetharama *et al.* 1984, Hargreaves 1984, etc.). Huda *et al.* (1984) and Huda (1987) have shown that the

two most critical aspects. *viz..* leaf area development and the dry matter partitioning are both related to the tillering response of millet. Franquin (1984) has shown that the duration and time of occurrence of the different development phases of millet depend on the planting date and photo-periodic response in relation to available water and pest incidence. In most of these models. no estimation of biomass by growth stages seems to have been made. These models also did not furnish geographical mapping of grain yields nor do they take into account incidence of insect pest and disease. Water use in pearl millet, particularly under less favourable conditions. is of considerable interest in areas of marginal water supplies. Some studies on water use by pearl millet have been conducted by agricultural scientists. Kanemasu *et al.* (1984) studied water use and water use efficiency (WUE) of pearl millet and observed that the WUE increases slightly with water stress. Dancette (1980) also found that in the short to medium duration millet. WUE increases with less water use.

In India. determination of water need of the crop and estimation of yield for pearl millet has not attracted the attention it deserves. In the present analysis. water use and water use efficiency of millet crop have been examined. An attempt has also been made to compute a yield index from water balance technique and its relationship with the actual yield determined.

2. Data set

India Meteorological Department (IMD) maintains a set of 39 evapotranspiration observatories which measures water loss of the different crops. At Hisar (29° 10' N. 75° 46'E) and Bellary (15° 19' N. 76° 51' E) located in the semi-arid track of India. pearl millet was grown only from 1979 to 1984 at Bellary and 1977 and 1979 to 1984 at Hisar. These data have been used in the study. The weather data was collected from the Agromet Observatory located close to the field at these locations. Crop yield data refers to that collected from the experimental field. From the daily data. weekly totals of various agro-meteorological parameters. from the date of sowing to maturity. were computed. At Hisar the soil is mainly loamy with yellowish brown colour having field capacity 25.0% and wilting point 8.5%. Around Bellary. soil is mostly clayey. having dark grey colour with a field capacity and wilting point of 35.0 and 10.0% respectively. The bulk density at Hisar and Bellary was 1.36 and 1.56 g/cm^3 respectively. The actual evapotranspiration data (ET) in this study have been obtained from

TABLE 1

Crop Information

Year	Variety	Sowing date	Harvest date
		Hisar	
1977	PHB-14	3 Jul	6 Oct
1979	BJ-104	28 Jul	13 Oct
1980	BJ-104	12 Aug	21 Oct
1981	BJ-104	29 Jul	11 Oct
1982	BJ-104	28 Jul	18 Oct
1983	BJ-104	14 Jul	2 Oct
1984	BJ-104	18 Jul	10 Oct
		Bellary	
1979	BJ-104	16 Jul	29 Sep
1980	BJ-104	17 Jul	25 Sep
1981	BJ-104	17 Jul	1 Oct
1982	BJ-104	17 Jul	17 Oct
1983	BJ-104	26 Jul	15 Oct
1984	BJ-104	24 Jul	17 Oct

gravimetric lysimeter. The lysimeter consists of a sensitive dormant type weighing machine. 1.3 × 1.3 × 0.9 m in size. of two tonne capacity, sunk in the middle of the crop field on a re-inforced concrete structure. The computed ET from the water balance methodology followed in this study is represented by ETA. The details of variety used, dates of sowing and maturity are given in Table 1.

3. Method of analysis

3.1. *Soil moisture balance technique*

In this study. soil moisture balance technique as given by Frere and Popov (1979) has been used.

Accordingly. if

S_i : water retained in the soil at the end of the *i*th week.

S_{i-1} : water retained in the soil at the end of the previous week,

P_i : precipitation during the *i*th week,

TABLE 2

Calculation of cumulative soil moisture balance

Station : Hisar, Year : 1983

Weeks	D_i (cm)	Sa_i (mm)	S_{i-1} Per D_i (mm)	Max D (mm)	P_i (mm)	Kcr_i	PET_i (mm)	WR_i (mm)	$P_i - WR_i$ (mm)	S_i Per D_i (mm)	S_i (max) (mm)	S_i/Sa_i	ETA/ WR_i	$S_i - Sa_i$ (mm)
1	10	17	17	132	2	0.30	46	14	−12	5	120	0.91	0.99	−12
2	20	33	21	120	6	0.40	41	16	−10	11	110	0.83	0.98	−22
3	30	50	27	110	74	0.50	50	25	49	76	159	1.00	1.00	27
4	40	66	93	159	58	0.60	41	25	34	126	192	1.00	1.00	60
5	50	83	143	192	2	0.70	34	24	−22	121	170	1.00	1.00	38
6	65	107	146	170	35	0.80	36	29	6	152	176	1.00	1.00	44
7	75	124	168	176	14	0.90	38	34	−20	148	156	1.00	1.00	24
8	80	132	156	156	66	1.00	41	41	25	181	181	1.00	1.00	49
9	80	132	181	181	1	1.10	39	42	−41	140	140	1.00	1.00	8
10	80	132	140	140	3	1.00	36	36	−34	106	106	0.80	0.97	−26
11	80	132	106	106	24	0.90	35	32	−8	99	99	0.75	0.96	−33
12	80	132	99	99	0	0.80	34	27	−27	71	71	0.54	0.88	−61
13	80	132	71	71	0	0.60	32	19	−19	52	52	0.40	0.78	−80

WR_i : water requirement of the crop during the ith week which is given by

$$WR_i = K_{cri} \times PET_i \qquad (1)$$

PET_i : potential evapotranspiration during the ith week and

K_{cri} : crop coefficient during the ith week, then

$$S_i = S_{i-1} + P_i - WR_i \qquad (2)$$

The potential evapotranspiration (PET) was calculated by using Penman's method as given by Doorenbos and Pruitt (1977). The crop coefficient (K_{cri}) values in the study were based on those given by Doorenbos and Kassam (1979). For a typical crop season at Hisar the computation of soil moisture balance is shown in Table 2.

3.2. *Rooting depth* (*D*)

Water uptake of crops is closely related to root distribution, particularly rooting depth. A close relationship exists between plants' ability to absorb water and the root system (Gliemeroth 1952). According to Olderman and Frere (1979), in well cultivated deep soils, roots of dry crops like maize could reach a depth of 2 m, but the highly branched mass of roots when the crop is well developed, is located in the upper 80 cm or so and around 80% of the soil water intake occurs within this depth.

In the present analysis also the maximum depth of pearl millet was assumed as 80 cm. According to Gregory and Reddy (1981), the maximum root depth for millet in medium soil is 90 cm while Thornthwaite and Mather (1957) assumed a depth of 80 cm for moderately deep rooted crops like millet in loam/clay soils. Olderman and Frere (1982), in their study of soil water balance of dry land crops like maize, assumed the maximum rooting depth of crop as 80 cm.

3.3. *Calculation of yield index*

The ultimate goal of establishing a cumulative soil water balance is to estimate the extent to which the water requirements of crops are met at any stage of the crop growth period. A yield index, taking into consideration of this fact, thus, furnishes an estimate of the likely yield at any stage of the growth (Frere and Popov 1979).
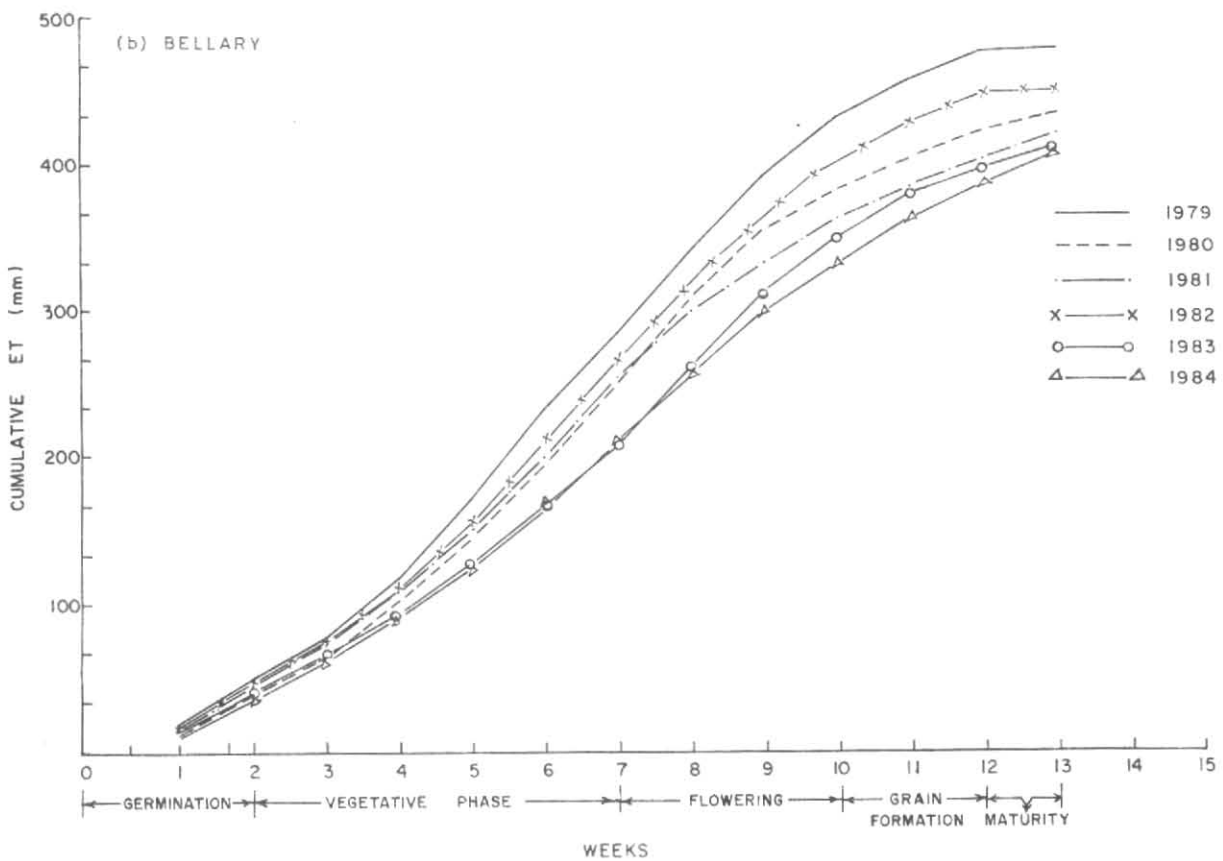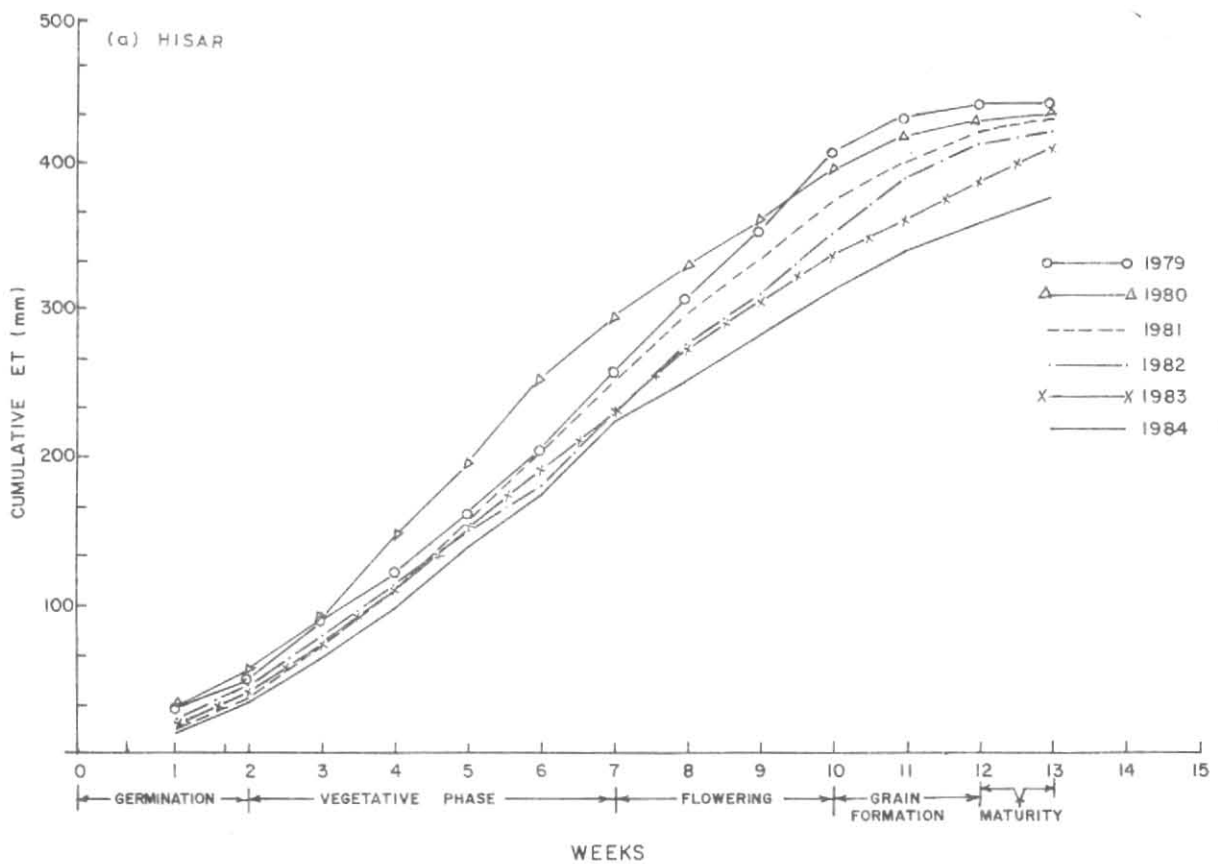
Figs. 1 (a & b). Cumulative evapotranspiration during different years for (a) Hisar & (b) Bellary

TABLE 3

Calculation of yield index (Y_i)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13
Y_{i-1} ($Y_0 = 100$)	100	99.8	99.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2	98.0	96.8	93.2
1−ETA/WR	.01	.02	0	0	0	0	0	0	0	.03	.04	.12	.22
$KY_i(1-ETA/WR_i)$ $= (1-Y_a/Y_m)$	.002	.006	0	0		0	0	0	0	.92	.012	.036	.044
$100 \times (1-Y_a/Y_m)$	.2	.6	0	0	0	0	0	0	0	1.2	1.2	3.6	4.4
$Y_i = Y_{i-1} - 100(1-Y_a/Y_m)$	99.8	99.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2	98.0	96.8	93.2	88.8
$(S_i - Sa_i)$	−12	−22	27	60	38	44	24	49	8	−26	33	−61	−80
If $(S_i - Sa_i) > 100$ $\rightarrow Y_i = Y_{i-1}^{-3}$	99.8	99.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2	98.0	96.8	93.2	88.8

The yield index is assumed equal to 100 at the beginning of the growth cycle. A relationship between the actual soil water content (S_i), the maximum soil water content (Sa_i), the crop evapo-transpiration (ETA) and the maximum crop evapotranspiration, as in Doorenbos and Pruitt (1977) is given below :

$$ETA/WR = 1.03 - e^{(-3.5 \times S_i/Sa_i)} \qquad (3)$$

ETA and WR are obtained from water balance as mentioned above.

As per the presumptions made in the analysis as long as ETA/WR is 1 or ($S_i - Sa_i$) is less than 100 mm, the soil water content satisfies the crop water requirement and the yield index remains 100. The reduction in yield index due to shortage of water is computed by calculating the water deficit for each of the weeks which is given by the difference between the actual soil water content (S_i) at a given week to the total available water content (Sa_i), i.e., ($S_i - Sa_i$). The percentage yield reduction for a particular week is given by $100 \times (S_i - Sa_i)/\sum WR$, where, $\sum WR$ is the sum of WR for each week which constitute the total crop water requirement of the crop for the whole growth period.

The index developed in the study reflects the cumulative stress endured by the crop through excess or deficit of water and is closely related to the final crop yield under normal situations. It allows a very satisfactory and early qualitative assessment of the yield.

Doorenbos and Kassam (1979) have established a relationship between the actual yield and potential yield in relation to the actual and potential crop evapotranspiration which is given by

$$(1 - Y_a/Y_m) = K_y (1 - ETA/WR) \qquad (4)$$

where,

Y_a — actual harvested crop yield,

Y_m — the maximum harvested yield (under no water stress).

K_y — yield response factor.

Yield response factor (K_y) was taken from the crop weather evaluation manual for India by Hargreaves et al. (1985).

The calculation of the yield index is shown in Table 3. This is based on the Table 2.

4. Results and discussions

4.1. *Water use during the growing period*

The cumulative evapotranspiration (ET) is shown in Figs. 1 (a & b) for all the years for both stations. At Hisar, the cumulative water consumption does not differ much till about 7 weeks after sowing (WAS) in different years except in 1980 when ET value increases abruptly from 3 WAS and is maintained till the maturity stage of the crop. In 1979, large ET could be seen from 7 WAS and after 9th week, overshadows the value of even 1980, finally attaining a value of about 441 mm. In 1984, the cumulative ET was found to be the lowest among all the years and the crop probably suffered from lack of moisture. The value attained by the crops during the year was about 380 mm.

TABLE 4

Mean weekly water use (mm) pattern during different growth phases and water use (%) as function of total ET

Stage	Hisar		Bellary	
	Mean weekly water use	Water use % of total ET	Mean weekly water use	Water use % of total ET
Germination (1st and 2nd week)	23	15.9	22	15.1
Vegetative phase (3rd to 7th week)	36	24.8	33	22.6
Flowering (8th to 10th week)	40	27.6	39	26.7
Grain formation (11th and 12th week)	28	19.3	32	21.9
Physiological maturity (13th week)	18	12.4	20	13.7

The week-to-week cumulative ET remained highest in 1979 at Bellary right from the germination stage. About 475 mm of water is used by millet during the year. The lowest cumulative ET was 410 mm reported in 1984. The difference in ET among all the years becomes marked 4 WAS onwards and reaches as high as 75 mm at physiological maturity period.

The mean weekly ET for 5 major growth stages is given in Table 4. By and large, ET in some of the stages for the two stations are comparable. The maximum ET use of about 40 mm occurs invariably during flowering. It is during this period only when largest percentage of total water is consumed, *i.e.*, about 27-28%. When the crop is actively growing, the water use at the two locations is substantially high, *i.e.*, 33-36 mm which constitute about a quarter of total water use. At the time of setting up of senescence process, the demand of water becomes less and does not exceed 15% of total water use.

4.2. *Water use efficiency*

The ratio of crop yield to evapotranspiration, known as water use efficiency (WUE), serves as a very useful tool in crop and variety selection for the maximum yield per unit of water consumed. The WUE is, thus, given by

$$WUE = Y/ET \qquad (5)$$

where,

Y — yield of crop and

ET — cumulative evapotranspiration during crop growth period.

The numerator or denominator in the above equation are not independent of each other and both are influenced independently by crop management and environmental factors. Y is also greatly dependent on moisture regime, more the water available to the crop, higher the yield.

The WUE of millet for different years has also been computed alongwith total ET and the yields. It is seen that the WUE varies little from year-to-year in case of both the stations. In Hisar, the value of WUE varies from 1.95 kg/ha/mm in 1984 to 3.08 kg/ha/mm in 1983. In 1983, inspite of comparatively low ET of 410 mm, the maximum yield of 1265 kg/ha was reported, giving the highest value of WUE. In Bellary WUE attained a minimum value of 1.58 kg/ha/mm in 1982 and maximum of 2.54 kg/ha/mm in 1981. The crop yield in 1984 was found to be comparatively on the higher side inspite of one of the lowest ET value reported and thus it increased the WUE value. The WUE at Hisar is, on an average, larger than that at Bellary indicating that the variety BJ-104 uses water more efficiently at the former location compared to the later. The year-to-year variations in WUE may be attributed to varying environmental conditions.

4.3. *Soil moisture balance and yield response*

Klaij and Vachand (1992) studied the seasonal soil moisture balance of pearl millet on the basis of

moisture measurements in Niger. Singh and Ramakrishna (1992) predicted the yield of pearl millet using climatic water balance parameters in Kutch region of India.

If the soil water content falls below certain level, the crop evapotranspiration (ETA) is smaller than the potential crop evapotranspiration. This implies that the crop development is delayed if water stress occurs. The yield is affected when the stress occurs during critical periods in the development of the crop, such as vegetative or the flowering phase for millet. However, some stress towards the final development stage can be beneficial. It has been assumed that stress occurs when 50% of the total available water is depleted. This value, however, varies from crop-to-crop. The potential evapotranspiration also influences the fraction to which the availble soil water can be depleted while maintaining the actual rate of evapotranspiration equal to the potential crop evapotranspiration (Doorenbos and Kassam 1979).

In the present study, the period of soil moisture stress during crop growth stage has been quantified and compared to the yield. For this purpose stress has been considered only between the reproductive stage and maturity. This, as is well known, in the most critical period and any stress during this interval adversely affects the crop. For the ith week the total available soil moisture (Sa_i) is defined as

$$Sa_i = 0.1 (S_f - S_w) \times D \qquad (6)$$

where.

S_f — soil moisture at field capacity (%),

S_w — soil moisture at wilting point (%) and

D is the rooting depth (cm) during ith week. Assigning different value to D consistent with the crop growth, Sa_i for different weeks can be calculated from Eqn. (6). Ratio of actual to the available soil moisture, S_i/Sa_i for any week provides an indication of water availability to crop at its rooting zone. In the study $S_i/Sa_i \leqslant 0.5$ was considered as a stress week (Olderman and Frere 1982).

The plot of the number of weeks of crop stress *versus* actual yield in shown in Fig. 2 for both the stations. The relationship between the two clearly appears linear both at Hisar and Bellary. The correlation coefficient between the number of stress weeks and yield was −0.84 for Hisar and −0.83 for Bellary and these are significant at 1% level. It is
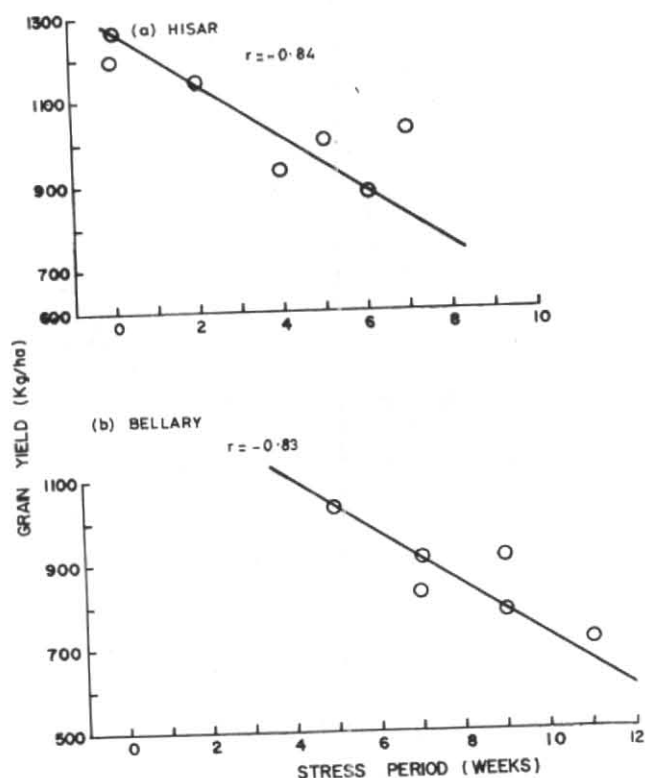
Figs. 2 (a & b). Relationship between stress period (weeks) and actual grain yield of (a) Hissar and (b) Bellary

obvious from above that the yield is inversely proportional to the stress period, the larger the stress duration, the lower is the yield.

Finally an excess of moisture in the root zone can also be harmful to the crop. Little information is available to express the quantity of excess soil moisture in terms of yield reduction percentage. According to Frere and Popov (1979) it is reasonable to consider that any excess of 100 mm or more (above the total available water) during a single decade will be reflected in a reduction of the yield index by 3 units, provided that the excess caused by precipitation falling on a short period of 2-3 days.

Having established a quantitative relationship to determine the yield reduction due to water stress as well as reduction due to excessive soil moisture, it is now possible to evaluate the yield index with the help of the Eqns. (3) and (4).

In order to find if the index proposed in the study in section 3.3 really represents conditions during growth and final yield, the actual yield from the observatory farm was regressed with the value of the index observed at the end of the crop season. The

following relation could be obtained for Hisar and Bellary.

$$Y = 4.92x + 714.07 \qquad \text{(For Hisar)} \qquad (7)$$

$$Y = 8.91x + 444.02 \qquad \text{(For Bellary)} \qquad (8)$$

when, Y is the grain yield in kg/ha and x is the yield index. For Hisar, the correlation coefficient was found 0.68 which is significant at 5% level and for Bellary, the same was 0.92 significant at 1% level. Thus, it appears possible to progressively monitor the crop growth as the season progresses and estimate the yield immediately at the end of the crop season from the yield index.

5. Conclusions

The following conclusions could be drawn from this study.

(*i*) The weekly water use by pearl millet is found to be the maximum (*i.e.*, 40 mm) during the flowering stage.

(*ii*) Water use efficiency of pearl millet reveals a fair degree of variability in time and space. The crop uses water more efficiently at Hisar than at Bellary.

(*iii*) Water requirement of the crop gradually increases with growth, attaining a peak during flowering stage.

(*iv*) The yield index was statistically found to give significant correlation with actual yield.

Acknowledgements

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